2004

# Performance evaluation of fabric aided slow sand filter.

Pulin Kumar Mondal
*University of Windsor*

# PERFORMANCE EVALUATION OF FABRIC AIDED SLOW SAND FILTER

By

Pulin Kumar Mondal

A Thesis
Submitted to the Faculty of Graduate Studies and Research
through Civil and Environmental Engineering in Partial
Fulfillment of the Requirements for the Degree
of Master of Applied Science at the
University of Windsor

Windsor, Ontario, Canada

2004

*Your file Votre référence*
*ISBN: 0-612-96402-7*
*Our file Notre référence*
*ISBN: 0-612-96402-7*

100B416

## ABSTRACT

Slow sand filtration is simple in technology and efficient in removing different pollutants, especially microorganisms and suspended particles. However, its application is limited to a narrow range of source water qualities and to certain operational features. High turbidity of water causes shorter filter run and frequent laborious filter cleaning. Several modifications have been developed and implemented to address these limitations of slow sand filters (SSF).

In this study, performance of non-woven synthetic fabric (NWF) aided SSF was evaluated in a laboratory scale setup. NWF was selected based on the specifications suggested in literature. Three filters with different thicknesses of fabric on sand beds and one filter without fabric were studied with simulated raw water prepared in laboratory.

The results revealed that there was no significant increase in filter run time for the filters with fabric as compared to the one without fabric. However, NWF captured most of the particles, and significantly protected the sand beds from particles deposition. The sand bed protection time was increased linearly with fabric depths. 22.3 mm thickness of selected NWF protected the sand bed for a longer period as compared to 8.9 mm thickness of fabric. Even though NWF showed no significant increase in filter run time, it allowed non sand-bed disturbing filter cleaning operation by protecting the sand bed. The fabric also supported the biogrowth and *schmutzdecke* development, which contributed to a significant portion (>60 %) of total organic carbon (TOC), total coliform and turbidity removal. Removing top one or more fabric layers, after previous filter runs, reduced the time required for filter ripening. Cleaning of fabric by pressurized tap water was convenient and restored the clean bed head loss.

High turbidity (9 to 12 NTU) in influent water shortened the filter run to 17 days as compared to 58 days with low turbidity (1 to 2 NTU). High TOC (4 to 9 mg/L) in influent water increased bioactivity in filters and thus enhanced filter ripening. However, excessive biogrowth due to high TOC shortened filter run time to 10 days. The overall removal performance of filters, with and without fabric, was comparable.

*To my Parents*

## ACKNOWLEDGEMENTS

The author is indebted to his advisors Dr. N. Biswas and Dr. R. Seth for their guidance and suggestions throughout this research and thesis writing. Without their timely advice and support this work would be incomplete.

Special thanks to Dr. J. K. Bewtra for his experienced suggestions in resolving many difficulties during this study and for being a part in reviewing the thesis. The author would like to thank Dr. A. V. Hubberstey for taking his time reviewing this thesis and being in the examination committee. The author would also like to thank Dr. N. K. Becker for his ideas and support during this work.

The technical assistance from the University Technical Support Centre is greatly appreciated. Lou Romano Wastewater Reclamation Plant is thankfully acknowledged for permitting access to the plant for sample collection.

The author expresses his deepest appreciation to his family and friends for their inspiration and support in countless ways for completion of this work.

Department of Civil and Environmental Engineering, Faculty of Graduate Studies and Research, and Natural Sciences and Engineering Research Council (NSERC) of Canada are thankfully acknowledged for the support during the development of this work.

# TABLE OF CONTENTS

## LIST OF TABLES

**Appendices**

# LIST OF FIGURES

**Appendices**

## LIST OF PLATES

**Chapter III**



**Chapter IV**



**Appendices**

## LIST OF APPENDICES

# LIST OF ABBREVIATIONS AND SYMBOLS

## Abbreviations

| | |
|---|---|
| AC | Activated Carbon |
| AOS | Apparent Opening Size |
| APHA | American Public Health Association |
| ASTM | American Society for Testing and Materials |
| AWWA | American Water Works Association |
| CAS | Chemical Abstract Service |
| CFU | Coliform Forming Unit (s) |
| DO | Dissolved Oxygen |
| ES | Effective Size |
| FC | Fecal Coliform |
| GAC | Granular Activated Carbon |
| IC | Inorganic Carbon |
| ID | Inner Diameter |
| NOS | Number of Samples |
| NTU | Nephelometric Turbidity Unit (s) |
| NWF | Non Woven Fabric |
| OD | Optical Density |
| P/A | Presence/ Absence |
| PVC | Poly Vinyl Chloride |
| SD | Standard Deviation |
| SSA | Specific Surface Area |
| SSF | Slow Sand Filter/Filtration |
| TC | Total Carbon |
| TOC | Total Organic Carbon |
| UC | Uniformity Coefficient |
| UV | Ultra-Violet |
| WEF | Water Environment Federation |

## Symbols

| | |
|---|---|
| CAT | Catalogue |
| G | Gravitational Acceleration |
| % | Percent |
| $^{o}C$ | Degree Celsius |
| Chl-A | Chlorophyll-A |
| d | Day (s) |
| $d_{10}$ | 10% Passing Diameter |
| $d_{60}$ | 60% Passing Diameter |
| $d_f$ | Fibre Diameter |
| $d_s$ | Filter Media Grain Diameter |
| $\varepsilon_o$ | Clean Bed/ Filter Media Porosity |
| $\phi$ | Sphericity Index |
| F1 | Filter 1 |
| F2 | Filter 2 |
| F3 | Filter 3 |
| F4 | Filter 4 |
| g | Gram (s) |
| $\gamma$ | Volume Fraction of Fibres in the Fabric |
| h | Hour (s) |
| H | Head Loss |
| k | Hydraulic Conductivity |
| kg | Kilogram (s) |
| $K_h$ | Permeability Factor |
| L | Litre (s) |
| m | Metre (s) |
| µg | Microgram (s) |
| mg | Milligram (s) |
| min | Minute (s) |
| mL | Millilitre (s) |
| µm | Micrometre (s) |
| mm | Millimetre (s) |
| N | Nitrogen |
| n | Number of Samples |

| | |
|---|---|
| $\nu$ | Kinematic Viscosity |
| $NH_3$ | Ammonia |
| $NO_3^-$ | Nitrate Ion |
| p | Porosity |
| Pt-Co | Platinum-Cobalt |
| $\rho_b$ | Fabric Bulk Density |
| $\rho_\phi$ | Fibre Specific Gravity |
| rpm | Revolution per minute |
| s | Second (s) |
| $S_o$ | Clean Bed Specific Surface Area |
| T | Temperature |
| t | Thickness of Sand Bed |
| $v_f$ | Filtration Rate |
| w | Fabric Weight per Unit Area |
| z | Nominal Fabric Thickness |

# Chapter I

# INTRODUCTION

## 1.1 General Background

Safe drinking water is of prime importance to human life. However, the availability of clean and safe drinking water is limited in every part of the world; especially in rural and suburban areas of developing and underdeveloped countries. The presence of inorganic and organic pollutants makes water unsafe. Particularly the presence of pathogenic organisms is the main threat. Thus, adequate removal of toxicants and complete destruction of pathogens (to control outbreaks of waterborne diseases) is the prime objective of any water treatment system.

Even with the advances in water treatment technology, outbreaks of waterborne disease have continued to occur till date. In fact, the occurrence of reported outbreaks as well as the number of cases of illness associated with those outbreaks are increasing (Fox and Lytle 1996). A recent outbreak of waterborne disease in Milwaukee caused illness to 403,000 people (Fox and Lytle 1996). In the years 1993 and 1994, there were 30 outbreaks associated with drinking water in the U. S. (Fox 1996). Out of these outbreaks, 21 were in small water supply systems, and only two were in large systems. The outbreaks related to small water systems consisted of both inorganic contamination (e.g., lead, nitrate, and fluoride) and microbial contamination (e.g., *Cryptosporidium parvum*, *Giardia lamblia*, *Shigella sonnei*, etc.). Recent outbreaks of waterborne disease in Walkerton, Ontario, and North Battlefield, Saskatchewan, have heightened awareness regarding water quality in Canada.

Generally, small water systems tend to deal with source water of inferior quality due to lack of ideal water sources, and, therefore, are under higher threats in treating and distributing drinking water. These problems are often exacerbated in small systems by the lack of the economies of scale. Thus, low cost water treatment options are very important.

Slow sand filter (SSF) is simple in technology and operation, and is considered one of the suitable and low cost treatment technologies for both developed and developing countries; particularly for small community water supplies (Huisman 1978; Paramasivam et al. 1981; Ellis 1987; Leland and Damewood 1990; Riesenberg et al. 1995). In 1980, the United Nations declared the International Drinking Water Supply and Sanitation Decade open, and the only treatment considered reliable and to be recommended for developing countries was slow sand filtration (AWWA 1991). Moreover, researches during last two decades revealed that *Giardia* cysts and *Cryptosporidium* oocysts were better removed in SSF (2 to 4 log) as compared to rapid sand filter (0.5 to 1 log) (Rachwal et al. 1996). Since numerous outbreaks, especially of *Giardia* cysts and *Cryptosporidium* oocysts in small water systems have been registered in recent decades (Fox 1996), slow sand filtration has gained renewed interest. Therefore, "The China Pro Bono Outreach Project"- a safe and sustainable water supply project for the rural people in China, organized by a group of engineers in Ontario, Canada, selected slow sand filtration as the main treatment process for the drinking water treatment plant. The project has involved the University of Windsor to come up with a simpler and improved technique of slow sand filtration. This initiated the present study.

Even though SSF is considered suitable for small water system, its application is limited to a very narrow range of source water qualities and to certain operational features. Higher turbidity of source water and excessive proliferation of algae during summer time increase the filter cleaning frequency by clogging the filter quickly, and thus the operation cost is increased (Burman 1961; Huisman and Wood 1974; Montiel 1988; AWWA 1991). During initial and after-cleaning filter run of SSF, filter maturation period causes loss of water because of lower treatment efficiency during this period (Cleasby 1991; Collins et al. 1991). Moreover, filter cleaning by scraping top sand is labour intensive, and it disturbs the biologically active sand bed, which prolongs filter maturation time and affects the treatment performance adversely (Huisman and Wood 1974; Bellamy et al 1985a; Ellis 1985a).

Several modifications have been developed and implemented to address the limitations of conventional slow sand filtration. The main objective of the modifications is to reduce the total load of impurities going directly into the sand bed by some form of pretreatment. The pre-treatment techniques, such as roughing filters, GAC Sandwich filter, pre-ozonation etc. extend the range of water quality suitable for slow sand filtration, but these adaptations increase the cost of construction and operation (Tanner and Ongerth 1990).

The use of a filter mat addresses both the modifications of filter media and the alternative filter cleaning methods. The use of non-woven synthetic fabric (NWF) as filter mat in SSF has been reported by Graham and Mbwette (1991), and Mbwette (1989). They suggested the specifications of NWF, which could be used in SSF to increase the filter run time. Klein and Berger (1994) reported the application of NWF in an artificial ground water recharge SSF plant. These studies demonstrated that the use of NWF in SSF as filter mat could be an alternative for simplifying operations and improving the economics of the process by extending filter runs. However, the effect of process parameters on the performance of the modified process and its wider applicability to surface water of different characteristics has not been fully evaluated.

The present study was carried out to extend the knowledge of applying NWF in SSF and to examine its effect on the use of SSF for more adverse surface raw water quality expected in many developing and under developed countries.

## 1.2 Objectives of the Research

The main objective of this research was to evaluate the performance of SSF with and without NWF on the surface of the sand bed. The specific objectives were to:

- Study the hydraulic behaviour, head loss development, and filter run time of SSF with and without NWF.

- Study the effect of NWF thickness on head loss development, filter run time, and quality of filtered water.

- Investigate the effect of different levels of influent water turbidity and total organic carbon (TOC) on the filter ripening time, run time, and treated water quality.

- Investigate the effect of filter cleaning by removal of fabric layers on head loss development and filter ripening time in subsequent filter run.

## 1.3 Scope

A laboratory scale experimental setup was used for this research project. The scope of the study was as follows:

1. Filter design criteria and raw water quality parameters were selected to represent conventional slow sand filter and simulated surface water in the laboratory, respectively.

2. Filter operation conditions were optimized in terms of flow control and feed water preparation and mixing frequency.

3. The filter head loss development, particle capturing and removal efficiencies were studied on SSF without and with varying thickness of NWF, under operating conditions of high turbidity and low TOC in the feed water.

4. The biological growth on filter beds of SSF, without and with varying thickness of NWF, and its effect on head loss development, filter ripening, filter run time, and filtered water quality were determined, under operating conditions of low turbidity and high TOC in the feed water.

5. The head loss development, removal efficiencies, filter ripening time, and run time were examined after cleaning filters, by removing top layers of fabric, under operating conditions of low turbidity and high TOC in the feed water.

6. Test on ease of cleaning a clogged fabric layer and its change in hydraulic properties were conducted.

### 1.4 Organization of the Thesis

This thesis is organized into five chapters. Chapter I is the introduction to this thesis. Chapter II is a review of literature related to fundamentals of slow sand filtration process, modifications introduced to slow sand filtration with emphasis on the application of NWF in SSF. Chapter III includes the experimental setup details, materials employed and methodology for the experiments. Chapter IV presents the results and discussion according to the various phases of experiments. Chapter V contains conclusions of the present study and recommendations for future work. A list of references of pertinent literature is included. Appendices include additional details of experimental methods, data and results to supplement the information presented in Chapter III and Chapter IV.

# Chapter II

# LITERATURE REVIEW

## 2.1 History and Practices of SSF

Slow sand filtration is considered to be one of the earliest technologies in the modern water treatment processes. It was initially developed by John Gibb at paisley in Scotland in 1804 for supplying pure water for his bleachery (Baker 1949). In 1827, Robert Thom improved the previous slow sand filtration design, and later in 1829 he and James Simpson at the Chelsea Water Company in London designed the model, which is still used in current practices (Ellis 1985a). Simpson made the basic design of a downflow filter and used scraping to remove the accumulated material. The hydraulic loading rate, sand size, sand bed depth, and other design parameters that he initiated became the basis for the practice that followed. The practice became so established by 1952 that the Metropolis Water Act was passed requiring all water from the River Thames to be filtered before being supplied to the public (Huisman and Wood 1974).

### 2.1.1 Practice in the Europe

In the continental Europe, slow sand filtration was widely applied for the treatment of urban water by the 1850s, with installations and dates as follows: Berlin, 1856; Altona, 1860; Zurich, 1884; Hamburg, 1893; and Budapest, 1894 (Hazen 1913, as cited in AWWA 1991). However, by 1920s, most urban water treatment works changed the pattern of use of SSF to secondary filtration by introducing rapid sand filters as a primary filtration step for high turbidity waters (Ridley 1967). At present, nearly all large urban water treatment plants using SSF at least apply the principle of double sand filtration. The decline in popularity of SSF in favour of rapid sand filters in Europe was very apparent by 1950s. However, today the treatment potential of slow sand filtration is demonstrated by the fact that many cities in Europe (e.g. Paris, Zurich, Amsterdam, Antwerp and London metropolitan) still use it as a secondary filtration step preceded by either rapid sand filters or microstrainers (Rachwal et al. 1984). Over 20% of the drinking water in the U.K. and 80% of all London water is still slow sand filtered (Bowles et al. 1983).

### 2.1.2 Practice in the North America

The application of slow sand filtration in the North America has been slow and faced reluctant acceptance, which is in sharp contrast to the European experiences (Logsdon and Fox 1988). The first SSF in the United States was installed in 1872 for the town of Poughkeepsie, New York, and was designed by James Kirkwood (Baker 1949). Installations followed at Hudson, New York, in 1874, St. Johnsbury, Vermont, in 1882, and Lawrence, Massachusetts, in 1894 (Logsdon and Fox 1988). However, the invention of subsequent development of rapid sand filtration in the 1880's in the U. S. A. generally discouraged the use of SSF in new water works to the extent that within a few years the use of rapid sand filters became almost universal there (McNair et al. 1987). The United States had about 20 SSF by 1899 and 100 by 1940 (Logsdon and Fox 1988). A preliminary report done by the American Slow Sand Association in 1994 identified 225 slow sand filter plants in the United States. While, SSF have continued to be successfully used in small scale water supply schemes serving rural communities. In fact, in these small communities, there has even been a significant construction of new SSF units during the last three decades (Slezak and Sims 1984).

### 2.1.3 Practice in the Developing Countries

The use of SSF in developing countries is also well documented (Huisman and Wood 1974; Van Dijk and Oomen 1978; Huisman 1978; Visscher et al. 1987). SSF has been advocated by the World Health Organization especially for use in less developed countries. Huisman and Wood in 1974 published a book to facilitate technology transfer to the developing countries. The design and construction manuals (Van Dijk and Oomen 1978; Visscher et al. 1987), and manual for SSF caretakers (Visscher and Veenstra 1985) were written with the same objective. In these countries, the use of SSF is considered to be particularly suitable for rural water supply schemes in view of the ease and simplicity of operation and maintenance. The merits of slow sand filtration for rural communities in developing countries are the same as for small communities anywhere. The technology is passive in nature and therefore does not depend upon active process control. In addition, the construction uses mostly local materials and can utilize local labour, thus providing economic benefits as well. However, often problems related to lack of community participation and proper training of operators are common. (AWWA 1991).

### 2.1.4 Renewed Interest

In the late 1970's and early 1980's, the potential for application of slow sand filtration in the United States and other parts of the world was well established, in part because of extensive applications in Europe. Limitations for use by large water utilities were recognized, but the process was still considered to be a strong candidate for the use in smaller systems. In addition, slow sand filtration's efficient removal of bacteria and virus was the basis for the expectations that it also might be effective for the removal of *Giardia* cysts (Logsdon and Fox 1988).

Researches during last two decades revealed that *Giardia* and *Cryptosporidium* are better removed in SSF (2 to 4 log) as compared to rapid sand filter (0.5 to 1 log) (Rachwal et al. 1996). As numerous outbreaks, especially *Giardia* cysts and *Cryptosporidium* oocysts (which were either unknown or not considered to be pathogens in the 1800s and early 1900s; Logsdon et al. 2002) in small water systems have been registered in recent decades (Fox 1996), slow sand filtration has gained renewed interest. In this regard, recent interest to carry out research work on SSF in the USA and Canada (Slezak and Sims 1984; Cleasby et al. 1984; Fox et al. 1984; Bellamy et al. 1985a, 1985b; Seelaus et al. 1986; McNair et al. 1987; Bryck 1987; Collins and Eighmy 1988; Hendricks 1988a, 1988b) is an encouraging development. Moreover, SSF is simple in design and operation, and efficient in removing microorganisms. Thus, the United Nations are recommending SSF for developing countries for last few decades.

## 2.2 Components and Design Criteria of SSF

One of the advantages of SSF is that its design and construction is very simple. The essential parts of SSF are the supernatant water reservoir to provide water head for gravity filtration, filter-bed consisting of sand, filter underdrainage system to collect the filtrate, filter box containing the previously stated parts, and a filter control system to regulate the rate of filtration. Figure 2.1 shows the different parts of a SSF and Table 2.1 shows the recommended design criteria.

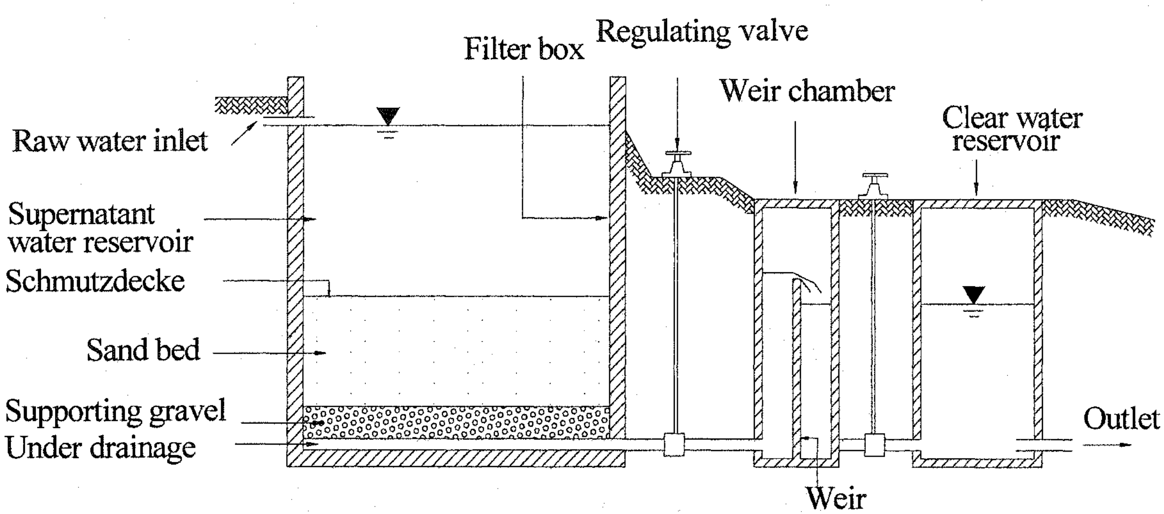



**Figure 2.1:** Components of SSF

* (Adapted from Huisman and Wood 1974)

**Table 2.1:** Recommended Design Criteria for SSF

| Design Criteria | Recommendations | | |
|---|---|---|---|
| | Ten States Standards | Huisman and Wood (1974) | Visscher et al. (1987) |
| Period of Operation, (h/d) | not stated | 24 | 24 |
| Filtration Rate, (m/h) | 0.08-0.24 | 0.1-0.4 | 0.1-0.2 |
| Depth of Filter Sand: (m)<br>Initial<br>Final Before Resanding | <br>0.8<br> | <br>1.2<br>0.7 | <br>0.8-0.9<br>0.5-0.6 |
| Specifications of Sand:<br>Effective Size, $d_{10}$, (mm)<br>Uniformity Coefficient, $d_{60}/d_{10}$ | <br>0.3-0.45<br>≤2.5 | <br>0.15-0.35<br>≤3, preferably <2 | <br>0.15-0.3<br>≤5, preferably <3 |
| Height of Underdrain Including Support Gravel Layer, (m) | 0.4-0.6 | not stated | 0.3-0.5 |
| Supernatant Water Height, (m) | >0.9 | 1-1.5 | 1 |
| Freeboard, (m) | not stated | 0.2-0.3 | not stated |
| Head Loss Permitted, (m) | not stated | not stated | 0.45-2 |

* Adapted from Pyper and Logsdon (1991).

### 2.3 Filtration Mechanisms

When a SSF operation is started for the first time with unused sand, the initial deposit on these sand grains is laid down by purely physical processes such as straining. As the deposit thickens, it creates a mat on top of the sand bed, which enhances removal of particles by the straining process. Due to other physical mechanisms, suspended particles, comprising of microorganisms, and other inorganic and organic particles, are attached to the sand grains and deposited mat. Physical mechanisms are significant when particles have been retained previously by the filter (within the bed or the developed layer), and considered to be caused by attachment of particles to the retained particles (Weber-Shirk and Dick 1997a). After a certain period of filtration, an adhesive film of microbial slime is formed on deposited mat and sand grains, which traps suspended particles more efficiently. The top deposited mat has been named "*schmutzdecke*" (German word for "dirty skin") which is a major habitat for the biological activities in SSF (Haarhoff and Cleasby 1991). It is characterized usually as gelatinous mat in which microorganisms thrive. This *schmutzdecke* and a layer of sand bed beneath are mainly responsible for the removal of impurities in SSF through a series of physical and biological mechanisms.

### 2.3.1 Physical Mechanisms

The principal physical mechanisms contributing to the particle removal in slow sand filtration are surface straining, transport and attachment.

#### 2.3.1.1 Surface Straining

Surface straining is the most obvious capture mechanism for particles too large to pass through the interstices between the grains. A clean sand of 0.2 mm effective size might be expected to capture particles about 30 μm in size by surface straining (Huisman and Wood 1974). This is substantially larger than many particles desired to be removed from surface water such as bacteria (0.3 to 10 μm), viruses (0.01 to 0.1 μm), colloidal particles (0.001 to 1 μm) (Montgomery 1985), *Giardia lamblia* cysts (10 μm), and *Cryptosporidium* oocysts (4 to 5 μm) (AWWA 1991). However, the water also contains some larger particles such as algae (30 to 50 μm for unicellular algae) and vegetative debris, which can be captured by surface straining. As particles are captured at the surface, the surface pore openings become smaller and surface straining is enhanced, allowing capture of smaller particles.

#### 2.3.1.2 Physical Mechanisms below the Sand Surface

The particles which escape capture at the surface, enter the pores of the filter bed. For these particles capture involves transport mechanisms to bring the particles to the grain surfaces and attachment mechanisms to hold the particles to the grain surfaces.

**Transport:** The transport mechanisms include interception, sedimentation and diffusion (Yao et al. 1971; Huisman and Wood 1974; AWWA 1991).

*Interception-* One way in which the particle may collide with the sand grain is through interception. An interception can occur only if a particle is carried by one of the streamlines of the flow closest to the sand grain, such that a brushing effect occurs.

*Sedimentation*- The force of gravity acts on all the particles, giving a vertical velocity component to the velocity of the particle. When the vertical velocity component is added vectorially with the convection velocity, the resultant velocity of the particle may cause it to collide with the sand grain. Sedimentation will have a perceptible role only for particles larger than 10 μm (Yao et al. 1971).

*Diffusion*- The thermal energy of liquid manifests in the form of random motion of molecules. When these molecules collide with a small particle, the particle will also move in a random fashion. The motion of the particle then occurs in a series of discrete steps. If the particle is being convected by a flow, then the diffusion is superimposed on the convection flow, and the particle moves from one streamline to another. Eventually, the particle may collide with a sand grain surface. Diffusion is of significant important for particles smaller that 1 μm (Yao et al. 1971).

**Attachment:** There is no removal within the sand bed without attachment. In most discussions of slow sand filtration, adsorption has been considered to be an important factor for attachment (Visscher et al. 1987; Huisman and Wood 1974; McConnell et al. 1984; Ellis 1985a). Huisman and Wood (1974) state that the electrostatic attraction, Van der Waal's forces and adhesion are frequently referred under the general heading of adsorption.

Colloidal particles of organic origin, including bacteria, usually have a negative charge and are consequently repelled; this is one of the reasons why such impurities are not removed when a filter with clear sand is first brought into service. While, during the initial ripening process positively charged colloidal particles including crystals of carbonates, flocculi of iron and aluminium hydroxide, and cations of iron, manganese aluminium and other metals (Huisman and Wood 1974) may accumulate on some of the filter grains to such an extent that oversaturation occurs with a consequent reversal of charge, rendering the grain and its attached particles positive. Adsorption on such grains is then able to remove negatively charged impurities, including colloidal matter of animal or vegetable origin and anions such as nitrate and phosphate and radicals, until over saturation again leads to charge reversal. This continuing charge reversal, once started, continues throughout the life of the filter bed (AWWA 1991).

Van der Waal's forces are very short range forces that can hold particles once they make contact with the grain surface or the surface of previously deposited material. But, these forces cannot function until the particle overcomes any electrostatic repulsion barrier and reaches the grain surface (Haarhoff and Cleasby 1991).

The microorganisms form a sticky gelatinous film on the surfaces of the sand grains, to which particles from the raw water tend to adhere when they are brought into contact by transport mechanism (Huisman and Wood 1974). When a filter is first started, and before a biofilm develops, the coliform removal is about zero (Bryck 1987). After a biofilm develops, the removal rate is 2-log to 4-log indicating the importance of the biofilm in slow sand filtration. Another theory is that extracellular enzymes from the developed biofilm coagulate the particles and permit attachment (Hendel et al. 2001). Bellamy et al. (1985b) hypothesized that these extracellular polymers facilitate destabilization of clay and bacteria to enhance the attachment of these particulates to the biofilms on the sand grains in the upper layers of the sand. This adhesion of the particles to the biofilm can be considered as combined action of physical and biological mechanisms.

### 2.3.2 Biological Mechanisms

The biological activities in a SSF contribute substantially to the filter performance (Ellis 1985a, 1985b). Following biological mechanisms have been suggested by different researchers:

*Predation-* Benthic invertebrates consume algae and diatoms, and strong evidence of bacterial grazing by protozoa was found (Burman and Lewin 1961; Richards 1974).

*Scavenging-* The detritus in SSF is scavenged mostly by aquatic worms that are found in the lower layers of the sand beds (Haarhoff and Cleasby 1991).

*Natural death/inactivation-* Most organisms die in a relatively hostile environment. It was found that the number of *E. coli* decreased as soon as they were introduced into the filter supernatant water (Haarhoff and Cleasby 1991).

*Metabolic breakdown-* It accounts for partial reduction of the organic compound. When biological particles attach to the biofilm, the microorganisms constituting the biofilm most likely metabolize them resulting in permanent removal of the contaminant particles (Huisman and Wood 1974).

Other biological mechanisms occurring during slow sand filtration are a*dsorption on biofilm, bactericidal effect of sunlight* (Gemeson and Saxon 1967), *bactericidal effect of algae* (Davis and Gloyna 1970), and *increased stickiness of sand surface* (Bellamy et al. 1985a, 1985b). The presence of a zoogleal layer on the sand surface can conceivably result in greater retention of colloidal particles, which explains why inorganic turbidity is better removed after filter ripening.

### 2.4 *Schmutzdecke*

*Schmutzdecke* is defined as a layer of material, both deposited and synthesized, on top of the filter bed that causes head loss disproportionate to its thickness and it is characterized usually as gelatinous mat in which microorganisms thrive and cause a major portion of the removal that occurs (AWWA 1991).

Huisman and Wood (1974) described the *schmutzdecke* as *"The Schmutzdecke consists of threadlike algae and numerous other forms of life, including plankton, diatoms, protozoa, rotifers, and bacteria. It is intensely active, the various microorganisms entrapping, digesting, and breaking down organic matter contained in the passing through. Dead algae from the water above and living bacteria in the raw water are alike consumed within this filter skin, and in the process simple inorganic salts are formed. At the same time nitrogenous compounds are broken down and nitrogen is oxidized. Some color is* *removed and a considerable proportion of inert suspended particles is mechanically strained out."*

Although the *schmutzdecke* has been described as a gelatinous zoogeal mass of living and dead microorganisms, its character can vary widely (AWWA 1991). It can also be a light, inert, black carbonaceous deposit or tightly packed and unattached to the sand with almost no biological growth depending on the raw water characteristics and environmental conditions. Bellamy et al. (1985b) did not find a well defined *schmutzdecke* in pilot filters at Colorado State University whereas Collins et al. (1990) reported that the *schmutzdeckes* at slow sand pilot filters in Portsmouth and Ashland, New Hampshire, were composed of gelatinous organic matter, which resembled the classic description. Whatever might be the character of the *schmutzdecke*, a deposit of some sort occurs in every SSF, which enhances particle removal efficiency and causes increase in the head loss. The *schmutzdecke* has a primary role in removal when it is composed of zoogleal mass and contains significant amount of bioactivity, and when it is merely a carbonaceous deposit accompanied with less bioactivity, the bioactivity in the sand bed is important for removal (AWWA 1991).

### 2.5 Filter Maturation/Ripening

The initial deposit on the sand bed is laid by a purely physical process. After a while, an adhesive film of bacterial slime is formed in the *schmutzdecke* and on the sand grain below the *schmutzdecke*. When the *schmutzdecke* is formed on top of the sand bed, it becomes an active habitat for the SSF organisms (Logsdon 1991a, 1991b). When the biofilm develops on the *schmutzdecke* and in the sand bed to its maximum extent for the given conditions, the filter is called mature, and the process is called filter maturatuin or ripening. Recent findings suggest that filter ripening resulting from the accumulation of particles within the filter bed (Weber-Shirk and Dick 1997a) and bacterivory (consumption of bacteria) by protozoa (Weber-Shirk and Dick 1997b, 1999) on, and in, the *schmutzdecke* is important for effective removal of organic matter and pathogens from raw water. There is an obvious problem in determining exactly when the point of filter maturity is reached. The period of filter ripening sometimes overlapped more than one filter run (Poynter and Slade 1977), which makes it difficult to separate maturation effects from filter clogging effects. Visscher et al. (1987) suggested that the absence of ammonia in the filtrate may signal complete bed ripening. The maturation period is shorter when more nutrients are available (Bellamy et al. 1985a). The water temperature can also be a factor during filter maturation; maturation was reached quicker at higher temperature (Poynter and Slade 1977).

Table 2.2 summarizes some of the reported maturation times indicated and defined by different researchers. As the table shows, there are widely differing definitions for filter maturation times and there is a lot of subjectivity involved in defining when the filter can be considered "ripened".

**Table 2.2:** Reported Maturation Times for SSF

| Study | Maturation Times | Defining Criteria |
|---|---|---|
| Poynter and Slade (1977) | 60 days | When viral removal was normal (> 98 %) |
| Sundaresan and Paramasivam (1982) | 35 days | Before *E. coli* was absent in the filtrate |
| Bowles et al. (1983) | 60 days | Before filtrate was less turbid than influent |
| Fox et al. (1984) | 40 days | Before total coliform counts were generally <1CFU/100 mL |
| Bellamy et al. (1985a) | 35-50 days | Before total coliform removal is stabilized (>99 %) |
| Bellamy et al. (1985a) | 280 days | Before *Giardia* removal went from 99 % to 100 % |
| Pyper (1985) | 100 days | Before erratic removal results disappeared |

* Adapted from Haarhoff and Cleasby (1991).

The traditional belief has been that the removal efficiency of SSF is solely due to biological activity of *schmutzdecke*. While, few recent reports suggest that the sand bed maturity is also important. Bellamy et al. (1985b) reported that at a hydraulic loading rate of 0.12 m/h in a pilot SSF, the total coliform removal was 3-log with a mature sand bed and *schmutzdecke*. When the *schmutzdecke* was removed carefully with less disturbance to the mature sand bed, the filter showed 2-log removal of coliform from the very beginning of the filter run.

**2.6 Filter Cleaning**

During normal operation, SSF slowly gets clogged due to the solids that are trapped on and within the sand bed, and formation of *schmutzdecke*. When the head loss in SSF builds up to its maximum allowable value, or the required flow rate cannot be maintained, the supernatant reservoir and top sand layer are drained and the top 15 to 30 mm of sand is scraped off and removed. This restores the hydraulic conductivity of the filter almost completely and the filter is ready for the next filter cycle. Most of the organisms are found in the *schmutzdecke* and in the sand layer directly beneath it. The filter scraping thus removes a large part of the population. During the first part of the next filter run, a certain waiting time is needed before the biological population is restored to its former value in the *schmutzdecke*. As a large part of the sand surface organisms are removed during scraping, it takes at least a few days before the population recovers. Some plants in New York Sate showed no scraping effects at all, while others showed a ripening period of 6 hours to 2 weeks (Letterman 1991; Cullen and Letterman 1985).

Cleaning of the bed may be carried out by hand or with mechanical equipment. During cleaning care should be taken to avoid disturbance of the sand bed below *schmutzdecke*. It was observed that bed disturbance during scraping had damaging effects on filter performance, and when the *schmutzdecke* was carefully removed in the experimental studies, it did not significantly affect the removal of viruses (McConnell et al. 1984), bacteria (Bellamy et al. 1985a) or turbidity (Fox et al. 1984). It was suggested that the scraping operation should be carried out as quickly as possible, preferably in one day to avoid detrimental effect on the biological population in the sand bed (Ellis 1985a; Huisman and Wood 1974).

The scraped sand does not need to be replaced until a specified minimum sand bed depth is reached. The recommended minimum bed depth is 0.5 m according to Visscher et al.

(1987) and Bellamy et al. (1985a), and 0.7 m according to Huisman and Wood (1974). After cleaning, the filter box is backfilled slowly with filtered water from the bottom to allow the air in the bed to escape. Air entrained within the bed can produce adverse effects on the filter performance.

After cleaning, the filter run is resumed, and the effluent is wasted for a period, usually for about 24 to 48 hours (Visscher 1990; Ellis 1985a). In some cases, instead of using a fixed filter-to-waste period, operators monitor the effluent quality, e.g., turbidity and coliform bacteria, to determine when the filter has reached the desired filtrate quality (Huisman and Wood 1974).

The frequency of scraping is site-specific and depends on available head, the media grain-size distribution, the influent water quality, and the water temperature (Letterman 1991). Surveys of slow sand filtration in the United States (Slezak and Sims 1984; Cullen and Letterman 1985) have shown that the frequency of scraping ranges from one week to one year. The average is about one and one-half months.

## 2.7 SSF Microorganisms

Microorganisms and their activities in SSF are distributed in three different zones of SSF. The first one is the body of water above the sand, which supports planktonic community. The second one is a community at the sand/water interface, consisting mostly of filamentous, attached organisms and detritus. The third is the interstices of the sand bed, which is called the benthic zone and the community is called a benthic community. The organisms present in these zones are mainly algae, protozoa, invertebrates, bacteria and viruses (Duncan 1988; Haarhoff and Cleasby 1991).

Among all these microorganisms, algae have been found to have both beneficial and detrimental effects on SSF performance. Algal growth of filamentous species contribute to the formation of an active *schmutzdecke* and zoogleal content of that forms a medium for trapping of particles. On the other hand, small algae, e.g. diatoms, contribute to poorly formed matting and cause a very rapid filter clogging (Huisman and Wood 1974).

Algae are the best characterized group of the SSF organisms. They can be categorized as diatoms, bluegreen, motile, planktonic and unicellular algae (Haarhoff and Cleasby 1991). The commonly reported SSF algae are grouped in Table 2.3.

**Table 2.3:** Commonly Reported SSF Algae

| **Group** | **Species** |
|---|---|
| * Unicellular, planktonic green | - *Chlorella, Scenedesmus* |
| * Unicellular, planktonic diatoms | - *Asterionella, Synedra* |
| * Unicellular, planktonic bluegreen | - *Microcystis* |
| * Motile, planktonic | - *Chlamydomonas, Navicula* |
| * Filamentous green | - *Spirogyra, Tribonema* |
| * Filamentous diatoms | - *Melosira, Fragilaria* |
| * Filamentous bluegreen | - *Anabaena, Oscillatoria* |

* Adapted from Haarhoff and Cleasby (1991).

All the planktonic species present in the filter influent and those planktonic organisms that grow within the supernatant reservoir itself are present in supernatant reservoir. The highest concentration of algae in the SSF appears in the *schmutzdecke* (Phillips et al. 1985; Bowles et al. 1983; Bellinger 1979). Within the sand bed, the algal concentration is highest immediately below the *schmutzdecke*. A pilot study in Australia found a high concentration of algae in the top 10 mm of sand, and below 80 mm practically no algae were found (Bowles et al. 1983). Thus, removal of the top sand layer of 20 to 30 mm, which is common during routine filter scraping, not only removes the *schmutzdecke*, but also the major part of the algae that are trapped in the sand.

## 2.8 Removal Performance of SSF

For acceptable quality of influent waters (presented in Section 2.10) and ripened filters, the documented performances of conventional SSF in removing various pollutants are summarized in Table 2.4.

**Table 2.4:** Removal Performance of SSF

| Water Quality Parameter | Treatment Performance |
|---|---|
| Turbidity | <1.0 NTU (remaining in filtrate) |
| Coliform | 90 to 99.9 % (removal) |
| Enteric Viruses | 99 to 99.99 % (removal) |
| *Giardia* cysts | 99 to 99.99 % (removal) |
| Total Organic Carbon (TOC)) | <15 to 25% (removal) |
| Biodegradable Dissolved Organic Carbon | <50% (removal) |
| Thrihalomethane Precursors | <25% (removal) |

* Adapted from Collins et al. (1991).

### 2.8.1 Removal of Microorganisms

SSF is very effective in removing microorganisms, including bacteria, viruses, and cysts.

*Bacteria:* Huisman and Wood (1974) suggested that the total bacteria count in water could be reduced by a factor of 1000 to 10000 and that the factor for the removal of *E. coli* varied between 100 and 1000, with usually none appearing in the filtrate. Van Dijk and Oomen (1978) found that between 99 and 99.9 % of pathogenic bacteria were removed during slow sand filtration. Poynter and Slade (1977), operating a laboratory scale SSF, found 99.6% removal of coliform organisms and 99.5 % removal of *E. coli.* Ellis (1985a) conducted studies on bench scale slow sand filters. It was observed that the slow sand filters gave consistent coliform removal greater than 95%. Cleasby et al. (1984) reported removal of total coliform of 99.7%. Fox et al. (1984), Bellamy et al. (1985a, 1985b), Bryck (1987), and Barrett and Silverstein (1988) have measured removals of total coliform bacteria, and the removal efficiencies were more than 99 % when mature filters were operated.

*Viruses:* SSF is capable of reducing the virus and enterovirus by 2 to 4 log units. According to a review by Lloyd et al. (1983), slow sand filtration was substantially more efficient than rapid sand filtration in virus removal. Their studies achieved a poliovirus reduction of 95 to 100% and MS2 coliphage reduction of 99.75 to 99.996%. Poynter and

Slade (1977) reported reduction in poliovirus1 of 98.25 to 99.99%. They concluded that virus removal was mainly due to adsorption to biomass, and the topmost *schmutzdecke* layer has the greatest contribution.

*Cysts:* Removals of *Giardia* cysts were determined by Bellamy et al. (1985b) in pilot filters. The effect of several independent variables including hydraulic loading rate, temperature, sand bed depth, sand size, nutrient addition, and intermittent chlorination, was investigated. In all cases, he reported more than 99.9% of *Giardia* cyst removal. Pyper (1985) reported more than 99.98 % removals of *Giardia* cysts under warm temperatures. Bryck (1987) found 99.998 % removals. Timms et al. (1995) reported that *Cyptosporidium* oocysts removal was better than 99.97 %. Palmateer et al. (1999) showed that the Manz intermittent SSF could remove 100% of *Giardia* cysts and 99.98% of *Cryptosporidium* oocysts when administered in the concentrations varying from 10 to100 times of the environmental pollution levels.

Despite the fact that several variables influenced the slow sand filtration process, removal efficiencies were high, generally more than 95% for all microbiological particles.

### 2.9 Variables Affecting Performance

The SSF process variables affecting the filter performance may be classified as: (a) design, (b) operating, and (c) ambient. Table 2.5 shows the specific variables under each category.

**Table 2.5:** Process Variables Affecting SSF Performance

| Category | Variables |
|---|---|
| Design | * Hydraulic loading rate<br>* Sand effective size and uniformity coefficient<br>* Head loss allowed<br>* Sand bed depth<br>* Filter shading |
| Operating | * Frequency of scraping<br>* Filter down time after scraping<br>* Minimum bed depth permitted<br>* Maturation time<br>* Flow variation<br>* Age and type of *schmutzdecke* |
| Ambient | * Water temperature<br>* Raw water quality (colour, turbidity etc.)<br>* Types of microorganisms<br>* Algae types and concentrations<br>* Turbidity characteristics and magnitude<br>* Organic compounds and concentrations<br>* Nutrients and concentrations |

* Adapted from Hendricks and Bellamy (1991).

Important parameters are discussed below:

***Temperature:*** The SSF removal efficiency generally decreases with declining ambient temperature in terms of coliform and standard plate count bacteria. Bellamy (1985a, 1985b) reported 92 % and 99.6% removals of total coliform bacteria for two filters under identical conditions except the different temperatures, $2^{o}C$ and $17^{o}C$, respectively.

***Nutrients:*** Nutrients are necessary for growth and activity of biopopulation within the filter. Bellamy et al. (1985a) reported that the filter with nutrients developed its biological community within a matter of days, versus weeks for the one with only ambient nutrient levels. Barrett and Silverstein (1988) reported that use of high carbon loadings (6 mg/L of glucose) in the influent at temperature $25^{o}C$ shortened the filter run to five days because of higher biological growth on the sand bed.

***Sand Bed Depth:*** The effluent water quality varies with the change in sand bed depth. The quality improves as the bed dept increases up to 0.65 m, beyond which no further significant improvement is found (Ellis 1987; Muhammad et al. 1996). Bellamy et al. (1985a) stated that coliform removals averaged 97% for a filter bed depth 0.98 m and declined to 95% for a filter bed depth of 0.48 m.

***Sand Size:*** Filter media of larger size within the design criteria increases pore sizes and allows particles to be driven deeper into the filter, thereby increasing the amount of medium to be scrapped. While, SSF with finer sand produce better quality water but reduce the length of filter run. Bellamy et al. (1985a) reported that percentage of removal was reduced from 99.4% for $d_{10} = 0.1$ mm to 96% for $d_{10} = 0.6$ mm.

Other than the factors discussed, hydraulic loading rate and covering SSF are reported to have significant effect on filter performance. Higher hydraulic loading decreases the removal efficiency of total coliform, standard plate counts and turbidity (Ellis 1987). Schellart (1988), and Huisman and Wood (1974) reported the benefits of covering SSF, in terms of longer filter runs and a reduction in algal proliferation.

## 2.10 Source Water Quality

Production of safe and attractive finished water and acceptable filtration cycle length for a SSF depend primarily on the source water quality apart from the SSF design parameters and environmental conditions.

*Colour:* SSF is not very efficient in removing the true colour from humic substances (Huisman and Wood 1974). Typical removal is 25% or less, thus, a source water limit of 5 to 10 Pt-Co colour units of true colour has been suggested by Cleasby et al. (1984).

*Suspended solids load:* The influent suspended solids loads are often expressed as turbidity (a surrogate indication). Turbidity is simple to measure, and most guidelines of acceptable source water for SSF are based on source water turbidity. Huisman and Wood

(1974) suggested that it was best if the turbidity was less than 10 mg/L as $SiO_2$, but that 100 to 200 mg/L could be handled for a few days. Ellis (1985a) summarized the recommendations of several reports, which suggested limits of turbidity of 10 to 50 NTU for short period and 50 to 120 NTU for 1 to 2 days.

*Organic Compounds:* Organic nutrients and plant nutrients in the source water impact the cycle length. Plant nutrients and solar radiation contribute to both algae production in the source water and to algae production within the filter supernatant water of open SSF. The algae have a pronounced effect on the filter cycle length with potentially much shorter cycles in the summer months (Schellart 1988). Chlorophyll A is often used as an indirect measurement of the amount of algae in the source water. Source water organic content (carbon source) also serves as a direct substrate for the bacteria, thereby increasing the clogging rate in the filter and shortening the cycle length.

The following guidelines for ideal source water quality, which should results in filter cycles of 1.5 to 2 months, have been suggested for SSF without pretreatment, by Cleasby (1991):

- Turbidity <5 NTU
- Algae- No heavy seasonal blooms,
  Chlorophyll A < 5 μg/L
- Iron < 0.3 mg/L, and
- Manganese < 0.05 mg/L.

For the waters exceeding the acceptable source water quality guidelines for SSF, a number of pretreatment methods, such as river bank/bed filtration, modular sub-sand abstraction system, plain sedimentation, tilted plate settling, downflow/upflow roughing filtration, horizontal flow roughing filtration, and pebble matrix filtration, have been used extensively in the past and a few methods are currently under study (Smet and Visscher 1989).

## 2.11 Modifications to Offset the Limitations of SSF

Apart form the design variables, there are several concerns which limit slow sand filtration as a viable treatment option. The three most noted concerns are: (1) a limited acceptability of raw waters containing moderate levels of abiotic or algal solids, (2) a limited ability to remove organic precursor materials, and (3) extensive filter downtimes and ripening periods. The main objectives of modifications are two fold. The first is to reduce the total load of impurities going directly in to the sand bed by some form of pretreatment which would in turn increase the filter run times thus reducing the costs and frequency of the cleaning the SSF bed. The second is to simplify the cleaning operations of the sand bed.

Several modifications have been developed and practiced to address the limitations/concerns of slow sand filtration. The modifications enhancing operational and treatment performances may be grouped into a) pre-treatment techniques, b) filter media upgrades, and c) alternative s*chmutzdecke* removal techniques. The pre-treatment techniques includes the use of microstrainers, storage of raw water, roughing filters and pre-ozonation (Montiel et al. 1988). Filter media modifications include the utilization of filter mat and surface amendments, and *schmutzdecke* cleaning techniques include the use of filter mats and filter harrowing. Collins et al. (1991) and AWWA (1991) have summarized suggested modifications, listed in Table 2.6, to deal with specific concerns.

**Table 2.6:** Slow Sand Filtration Modifications that Enhance Performance

| **Concern** | **Modifications** |
|---|---|
| Adverse raw water quality | Roughing filter, Filter mats,<br>Pre-Settling |
| Presence of organic precursor | Preozonation,<br>Surface amendments,<br>Enhanced filter bed populations |
| Low filter run time, and high filter ripening time | Filter mats<br>Filter-*schmutzdecke* harrowing |

Some of the listed modifications are described in the following paragraphs.

*Roughing Filters:* Roughing filters significantly reduce raw water turbidity, coliform bacteria, and algal content. Wegelin (1984 and 1986) have reported the potential of using horizontal roughing filters as a pretreatment process, and this process removed most microorganisms in the size range of 0.5 to 60 μm, after 30 days of filter operations.

*Filter mats:* Filter mats placed on top of the sand surface provide longer filter run times and a simpler filter cleaning technique that involves the removal and cleaning of the fabric only. The main concern associated with this modification is the lack of application to raw waters of varying quality. Mbwette (1989) found longer filter run time with NWF as a mat on sand surface as compared to filter without NWF on sand bed.

*Preozonation:* Preozonation may increase organic precursor removals in SSF by increasing the production of more biodegradable compounds from large organic molecules that are more resistant to biodegradation. Greaves et al. (1988) have studied the potential of ozonation and subsequent slow sand filtration for the treatment of coloured waters. The pilot plant investigations showed that preozonation achieved significant reduction in colour, though the turbidity was not significantly reduced.

*Surface amendments:* A layer of anionic resin or granular activated carbon in SSF sand bed removes organic precursor significantly. The main disadvantage is that head loss development is rapid (AWWA 1991).

*Filter harrowing:* The process has been discussed in filter cleaning section (Section 2.6). Filter harrowing requires less time and manpower for filter cleaning. As this method maintains the bacterial population of the filter, a harrowed filter can be quickly placed back on line after cleaning, without deterioration in treatment performance (AWWA 1991).

## 2.12 Non-Woven Synthetic Fabric Use in SSF

Mbwette (1989), and Graham and Mbwette (1991) reported that operational performance of SSF could be considerably improved by the application of layer of non-woven fabric (NWF) to the top surface of the sand media. The rationale behind applying NWF layer to the top of SSF bed was to concentrate the treatment process within the fabric layer instead of within the top sand layer. NWF was considered more efficient filtration media than sand because of its greater porosity and specific surface area. An analysis of data from pilot SSF plant suggested that run time was increased by a factor of 1.5 to 2 by using 2, 4, and 6 layers of NWF (21.6 mm, 14.4 mm, and 7.2 mm thickness, respectively, and 14,430 $m^2/m^3$ specific surface area) on top of sand bed. The run time was increased with increasing fabric depth. In their study, they considered 350 mm of filter head loss as the end point of the filter run. Surface water of 1.1 to 4.4 NTU (average = 2.3 NTU) turbidity was used, and the average filtrate turbidities achieved were always less than 0.25 NTU. The average removal efficiencies were >78 % for particles of 4 to 64 μm size range and > 98% for total coliform. Based on this study, they suggested that fabric specifications of 13,000 to 15,000 $m^2/m^3$ specific surface area, and 30 mm of total fabric thickness were suitable for use in SSF.

Klein and Berger (1994) have reported the application of NWF at the Hardhof artificial ground water recharge SSF plant in Zurich. Geotextile was put on top of the filter bed to protect the sand against sunlight, and prevent algae and their organic and inorganic by-products from clogging the filter. They reported that geotextile in the Hardhof artificial recharge plant increased the running time by a factor of 10 when compared to a similar facility with no geotextile in the same city. The geotextile prevented the deposit material from penetrating the sand layer, and caused an essential part of head loss. This was demonstrated by almost complete recovery of the available head loss after replacement of the geotextile. They suggested the specific characteristics for the fabric as of high porosity between 70 to 95%, and pore size of about 0.1 mm. Since the application of NWF was for artificial ground water recharge, the findings might not be appropriate for the application of NWF in SSF.

Graham et al. (1996) reported that use of NWF on the surface of 0.50, 0.30 and 0.20 m layers of sand bed reduced the treatment performance systematically as bed depth decreased. However, under the test conditions, the filtrate quality from the 0.20 m filter was broadly consistent with WHO (1985) recommendations, and this 0.20 m filter protected with fabric was able to meet the treatment objectives for enteroviruses and *Cryptosporidium*.

### 2.13 Non-Woven Synthetic Fabric Properties

The term synthetic fabric refers to man-made textiles in the sense that the components which form the textile (i.e. fibres, webs or yarns) are produced synthetically. In general, synthetic fabrics can be subdivided into three groups; woven, non-woven and composites. Non-woven synthetic fabric is mainly used for various filtration applications (Giroud 1985). NWF include all the fabrics which are manufactured directly from fibres or webs without the need to produce yarns. They are usually said to be produced by fibre-bonding (Purdy 1979, Sandstedt 1979). NWF with fibres oriented in one direction only can be given additional structural integrity by thermal or chemically induced fibre fusion, needle-felting or application of adhesives or resins on the surface (McDonald 1971).

Literature suggests that in the commercial market, Polypropylene dominates the NWF field (Fletcher1979). Some of the most common advantages of using Polypropylene fibres are listed below:

- It has an excellent resistance to most chemicals, alkalis, acids and oxidizing agents found in drinking water treatment.
- Since it is free of polar groups (like amides in Nylon and esters in Polyester), it has a good fibre stain resistance and hence should be easier to clean when dirty.
- It has sufficient resistance to fungus and organic acids.

In almost all the cases, the mechanical strength of fabric is an important factor in relation to handling during washing.

Needle-punching, wet-bonded, dry-bonded, spun-bonded, and spun-lacing have been identified as the production processes of NWF (Cook 1984; Giroud 1985; Lunenschloss and Albrecht 1985; McDonald 1971; Sandstedt 1979). Out of these five types of NWF, needle-punched NWF is the most suited for the use in SSF as it provides higher porosity and specific surface area (Mbwette 1989). In needle-punching process, a needle-loom with a set of barbed hooks is repeatedly punched through fibre webs laid by carding or garneting. These needles cause fibres to become entangled tightly together in a three dimensional network (McDonald 1971).

### 2.13.1 NWF Physical Properties

In order to employ a fabric layer, it is necessary to characterize a fabric in terms of appropriate measurable properties. The properties of NWF that are particularly important are the porosity, mean fibre diameter and specific fibre surface area from the perspective of using as protective layer in SSF. For a particular fabric, the porosity and specific fibre surface area can be calculated from the fabric bulk density, mean fibre diameter and fibre density by using the following relationships, assuming the fibres to be cylindrical and the diameter to be reasonably uniform (Mbwette and Graham 1988):

$$\varepsilon_0 = 1 - \left(\frac{\rho_b}{\rho_f}\right) \quad \text{.......... (2.1)}$$

$$\rho_b = \frac{w}{z} \quad \text{.......... (2.2)}$$

$$S_0 = \frac{4(1-\varepsilon_0)}{d_f} \quad \text{.......... (2.3)}$$

where,

$\rho_b$ = Fabric bulk density

$\rho_f$ = Fibre density

z = Fabric thickness

$d_f$ = Fibre diameter

$w$ = Fabric mass per unit area

$\varepsilon_o$ = Clean bed porosity, and

$S_0$ = Clean bed specific surface area.

### 2.13.2 NWF Hydraulic Properties

An important property of any filter medium is its "permeability". According to Darcy's Law, permeability is a measure of the medium's resistance to pore flow. For deep bed granular media, the permeability can be expressed mathematically in terms of the properties of the media by combining the Kozeny-Carman Equation and Darcy's Equation. However, for media of high porosity such as fibrous media ($\varepsilon_o$ >0.7), Kozeny's Equation does not apply. Three models commonly used for theoretical prediction of permeability and pressure drop across fibrous media can be found in literature by Happel (1959), and Spielman and Goren (1968). The first one is based on equations of creeping flow and are referred to as cell models. It was found that the model of Happel (1959) gave theoretical permeabilities which agreed closely with experimentally determined values for commercial NWF (Graham and Mbwette 1991). These models are based on the assumption that the fibres are randomly oriented in a transverse plane to the fluid flow and provide an explicit expression for the permeability in terms of the fibre size and media porosity:

$$K_h = d_f^2 \frac{\left[ -\ln\gamma - \dfrac{(1-\gamma^2)}{(1+\gamma^2)} \right]}{32\gamma} \quad \text{..............(2.4)}$$

where,

$K_h$ = Permeability factor (=kν/G)

k = Hydraulic conductivity

ν = Kinematic viscosity

G = Gravitational acceleration, and

γ = Fibre volume fraction.

Happel's model shows that the hydraulic conductivity is quite sensitive to the magnitude of the fabric porosity. For example, a fabric of porosity of 0.9 has a theoretical hydraulic conductivity approximately 4 times that of a fabric of porosity 0.80. In general, commercial NWF have a porosity greater than 0.7 and consequently they have hydraulic conductivity considerably higher than typical sand media in SSF (Mbwette 1989).

### 2.14 NWF Filtration Mechanisms

The fundamental transport mechanisms discussed previously for slow sand filtration can be applied within NWF aided SSF beds, depending on the fabric manufacturing technique, physical and chemical composition, and characteristics of the raw water to be filtered. In NWF, surface filtration, depth filtration, adsorptive filtration and biological filtration phenomena can be identified (Mbwette 1989).

*Surface Filtration-* This involves straining of particles larger than pore sizes. Occasionally small particles, which arrive at the fabric surface simultaneously, are removed by bridging the pore. An additional surface filtration related phenomenon is the deposition of particles on the NWF surface because of sedimentation taking place due to the long detention time of supernatant water.

*Depth Filtration-* This occurs when particles penetrate the filter medium and become trapped in the tortuous paths due to its winding nature or fibre roughness. Obviously, a particle with a diameter smaller than the pore opening will be trapped in the fabric if its pore diameter narrows with depth. Increasing the depth of the fabric increases the predominance of this phenomenon.

*Adsorptive Filtration-* This involves removal of particles when they come in contact with and adhere to the fibre surfaces. This takes place throughout the fabric volume, and particles smaller than pore sizes are retained due to diffusional movements related to Brownian motions of submicron particles. Favourable fibre-particle surface charge characteristics encourage this phenomenon. An efficient adsorptive filter has to present a large surface area to the particles to increase the particle capture probability. NWF exhibit high specific surfaces, thus indicating their high adsorption potential.

*Biological Filtration-* This is expected to take place on surface and in the depth of the fabric. The formation of the surface biological layer in the top layer(s) of the NWF and around all fibres during ripening stage is expected to intensify straining and removal of unwanted particles. Further biochemical activities are expected to take place throughout the fabric depth involving oxidative processes and activities of living organisms. Biological activities are also expected to increase the adhesion probability of submicron particles.

# Chapter III

# MATERIALS AND METHODS

## 3.1 General

The experimental setup and the methods employed in the study are described in this chapter. Specifically, it includes experimental setup and selection of operational parameters for laboratory scale SSF, filter operation procedures, materials employed, different experimental phases and the analytical methods used to determine different water quality and filter operational parameters.

## 3.2 Selection of Filter Design Parameters

SSF design and operation parameters vary over wide range in values. The commonly accepted and practiced SSF design parameters have been shown in Table 2.1 of Chapter II. Based on this information, the design parameters for the laboratory SSF units, used in present study, were selected. These parameters are shown in Table 3.1.

Four filters were constructed; one with no fabric layer on top of sand bed and others with varying depths of NWF, achieved by varying number of layers. The first filter was designed to represent the conventional SSF, which was the control filter for the experiments. The number of fabric layers and total fabric thickness in other filters are shown in Table 3.2.

Four filters were built to compare between conventional SSF and SSF with fabric on top of sand bed and to study the filter performance with various fabric thicknesses.

**Table 3.1:** Selected SSF Design and Operation Parameters for the Present Study

| Parameters | Selected Values |
|---|---|
| Period of Operation | 24 h/d |
| Filtration Rate | 0.1 m/h |
| Depth of Filter Sand | 0.9 m |
| Specification of Sand:<br>Effective Size<br>Uniformity Coefficient | <br>0.28 mm<br>1.88 |
| Height of Underdrain Including Gravel Layer | 100 mm |
| Specification of Support Gravel:<br>Effective Size<br>Uniformity Coefficient | <br>3.47 mm<br>1.47 |
| Height of Supernatant Water | 1.1 m |
| Free Board | 150 mm |
| Column Diameter | 150 mm |
| Filter Surface Area | 17,670 $mm^2$ |
| Fabric Specifications:<br>AOS<br>Thickness/Layer<br>SSA<br>Porosity | <br>0.15 mm<br>4.45 mm<br>14,830 $m^2/m^3$<br>87 % |
| Head Loss Permitted | 1.05 m |

AOS-Apparent opening size, SSA-Specific surface area

**Table 3.2:** Filter Configurations in Terms of Fabric Thickness

| Filter | Number of Fabric Layers on top of Sand Bed | Total Fabric Thickness (mm) |
|---|---|---|
| F1 | 0 | 0 |
| F2 | 2 | 8.9 |
| F3 | 5 | 22.3 |
| F4 | 10 | 44.5 |

### 3.3 Filter Media and Support Gravel

Filtration sand and non-woven synthetic fabric were used as the filter media, and gravel and fabric were used as filter media support.

#### 3.3.1 Filter Sand

The filtration sand was obtained from the Northern Gravel Company, U. S. A. According to the manufacturer, this sand met all the American Water Works Association (AWWA) recommendations (AWWA document reference number: AWWA B 100-96) for filter sand. Chemically, the sand was composed of 99.48 % silica and 0.52 % other metal oxides. Particle size analysis was done in the laboratory and the effective size ($d_{10}$) and uniformity coefficient (UC) were determined to be 0.28 mm and 1.88 respectively. Particle size distribution of sand media, physical properties, chemical properties, and chemical composition are shown in Appendix A.

#### 3.3.2 Non-Woven Fabric

NWF for the present study was targeted for 80% or more porosity and 13,000 to 15,000 $m^2/m^3$ specific surface area (SSA) as per the recommendations of Graham and Mbwette (1991). Specific surface area, porosity and fibre diameter were calculated for several products from different manufacturers. The calculation of SSA, porosity and fibre diameter for different products are shown in Appendix B. Based on these information, the fabric TC Mirafi S1600 from Ten Cate Nicolon Company, U. S. A., was selected for use in this study. TC Mirafi S1600 is a non-woven geotextile composed of polypropylene fibre, which forms a stable network such that the fibres retain their relative position. According to the manufacturer, S1600 is inert to biological degradation and resistant to naturally encountered chemicals, alkalis, and acids. The mechanical properties of the selected fabric are shown in Table 3.3.

**Table 3.3:** Mechanical Properties of NWF TC Mirafi S1600

| Mechanical Properties | Test Method | Unit | Average Roll value |
|---|---|---|---|
| Mass | ASTM D 5261 | $g/m^2$ | 543 |
| Thickness | ASTM D 5199 | mm | 4.45 |
| Apparent Opening Size (AOS) | ASTM D 4751 | mm | 0.15 |
| Permeability | ASTM D 4491 | m/h | 11.2 |
| Flow Rate | ASTM D 4491 | $L/min/m^2$ | 2,036 |
| Fibre diameter | Calculated | mm | 0.036 |
| Porosity | Calculated | % | 87 |
| Specific Surface Area (SSA) | Calculated | $m^2/m^3$ | 14,830 |

* The fabric properties were provided by the manufacturer.

The fabric was cut by using a brass cutting dice of 150 mm ID. This cutting dice was fabricated at the Technical Support Centre of the University of Windsor. The dice was placed on the sample fabric and load was applied on the dice using the Tinus Olsen Universal Testing Machine. Plate 3.1 shows the fabric cutting by using the loading machine. The diameter of all fabric samples was found to be 150 ± 0.5 mm.

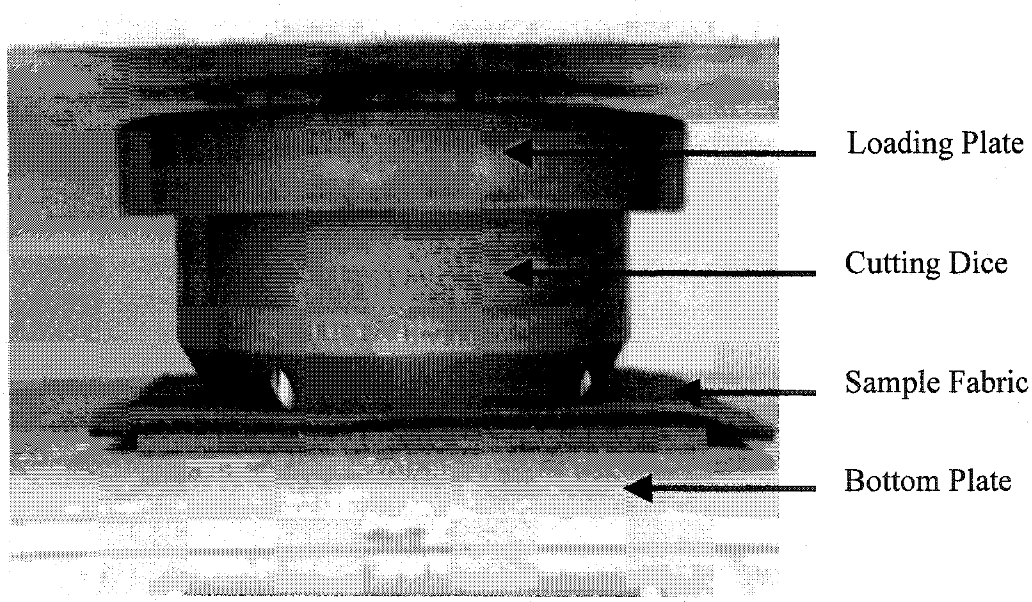



**Plate 3.1:** Fabric Cutting Device and Cutting in a Loading Machine

### 3.3.3 Support Gravel

The support gravel for the filter media was obtained from Northern Gravel Company, Muscatine, Iowa, U. S. A. According to the provider, the size range of the support gravel was 3 to 6 mm. The effective size (ES) of gravel was 3.47 mm and the uniformity coefficient (UC) was 1.47.

## 3.4 Experimental Setup

A laboratory scale experimental setup was built to conduct all the experiments for the current study.

### 3.4.1 Layout Design

Figure 3.1 shows a simple line diagram of the experimental setup and Figure 3.2 shows the detailed schematic layout of the filters and other components. Some pictures of the laboratory installation of the experimental setup are shown in Plate 3.2. The setup was built by using two different locations on two separate floors in Essex Hall, University of Windsor.

The second floor (235 Essex Hall) housed a 450 L (0.75 m in height and 1.1 m in diameter) cylindrical polypropylene mixing tank, a 600 L (0.9 m in height and 1.1 m in diameter) cylindrical polypropylene feed tank, distribution manifold and four flow controlling needle valves, an Advantage III activated carbon filter unit, a 20 L/min capacity Star Water Works (Model HPP 360) centrifugal pump for transferring water from mixing tank to the feed tank and two Phipps & Bird (Model 7790-400) stirrers. Each of the stirrers had 3 impellers on a 0.9 m long stainless shaft. The impellers were vertical flat blade type with 4 blades (blade size: 25 mm x 20 mm), and 120 mm in diameter. One stirrer was used for mixing during raw water preparation and other was used in feed tank to avoid sedimentation of particles.

The first floor (135 Essex Hall) housed four 2.5 m high SSF columns, a 450 L cylindrical polypropylene filter over flow tank, a 150 L cylindrical polypropylene filtrate collection tank, a centrifugal pump for recycling filter over flow from the over flow tank to the feed tank at the second floor, a wooden board containing all the piezometers and water sampling ports, constant water level filter outlet devices, and outlet filtration rate control valves.

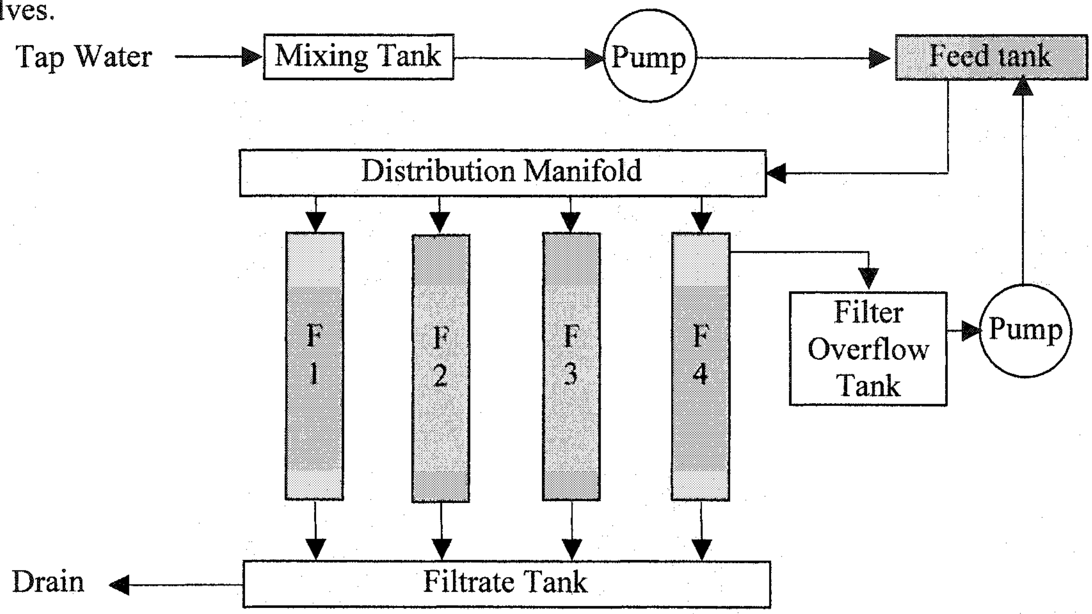



**Figure 3.1:** Line Diagram of the Experimental Setup

### 3.4.2 Installation of the Filters

Figure 3.3 shows the details of a single SSF unit. Each unit was fabricated in two parts to provide convenience in filter media placement and filter cleaning. The bottom part was a clear acrylic tube of 1.2 m length, 150 mm internal diameter and 6.5 mm wall thickness and was covered on the outside with aluminium foil to prevent photosynthetic activity during the experiments. The top part was an opaque acrylonitrile butadiene styrene (ABS) tube of 1.25 m length and 150 mm internal diameter. These two parts were connected with a water leak proof tube coupling connector. All filters were installed on a movable steel frame base covered with high-density polyethylene sheet. The acrylic bottom part of filter column had a 25 mm wide and 10 mm thick acrylic flange. This part was attached to the polyethylene base plate by using 6 bolts. A rubber O-ring was inserted in a groove on the flange to make the junction water leak proof.

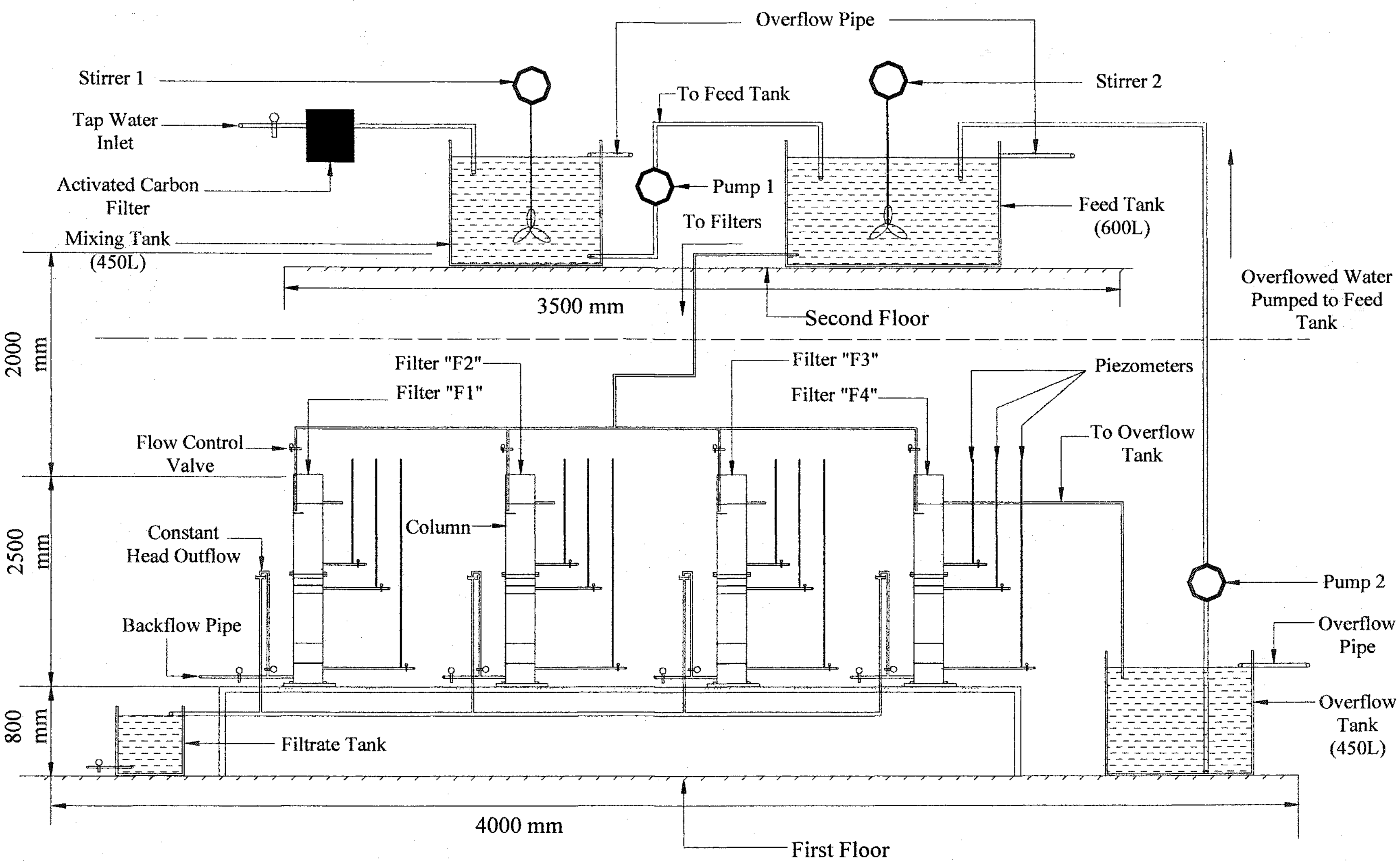
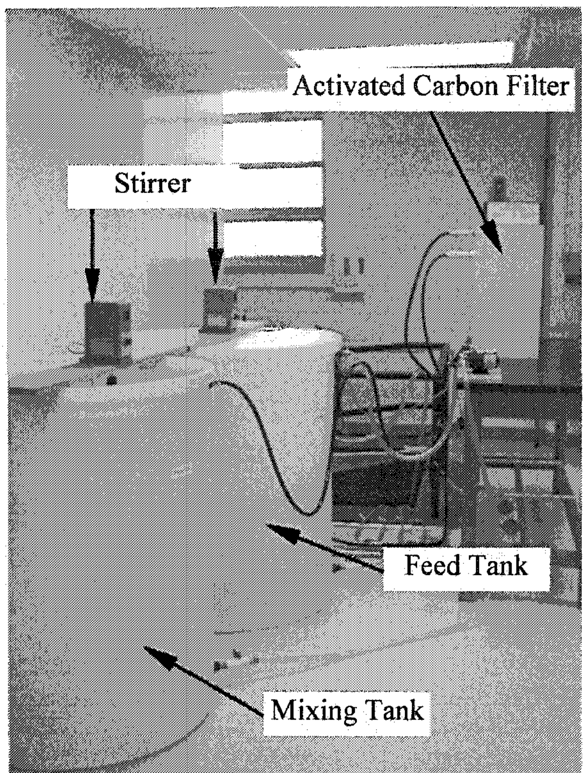
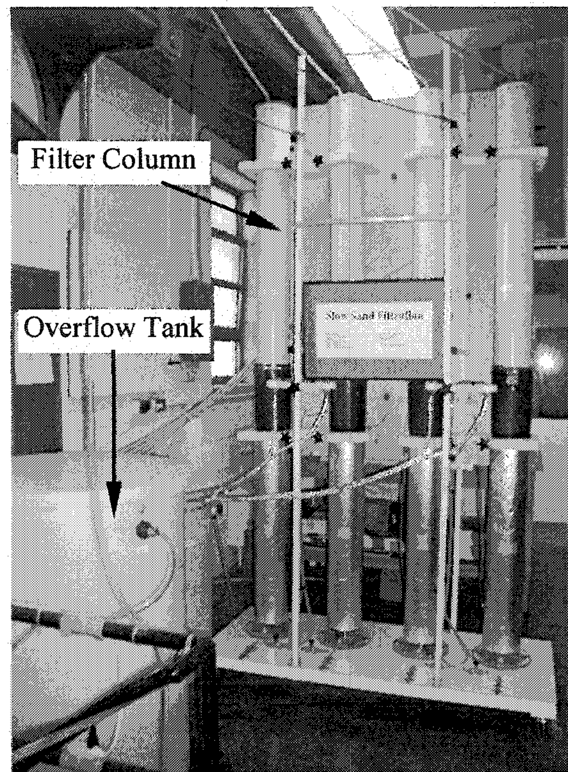


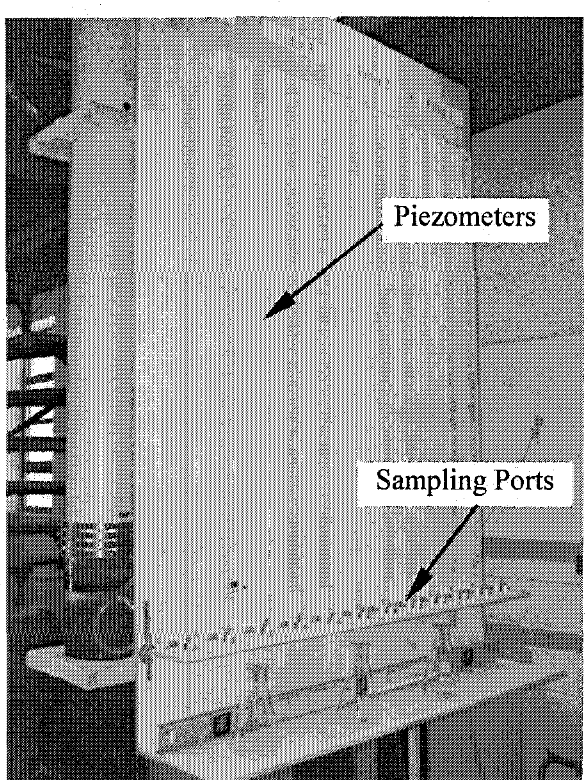

**Figure 3.2:** Schematic Diagram of the Experimental Setup



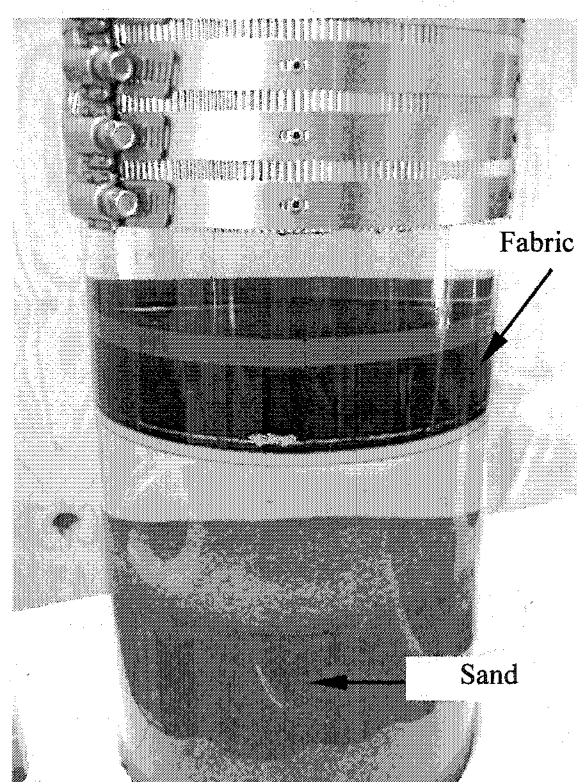
2nd Floor Experimental Setup



1st Floor Experimental Setup



Piezometers Board and Sampling Ports



Installation of Fabric Layers on Top of Sand Bed

**Plate 3.2:** Pictures of Some Parts of the Experimental Setup

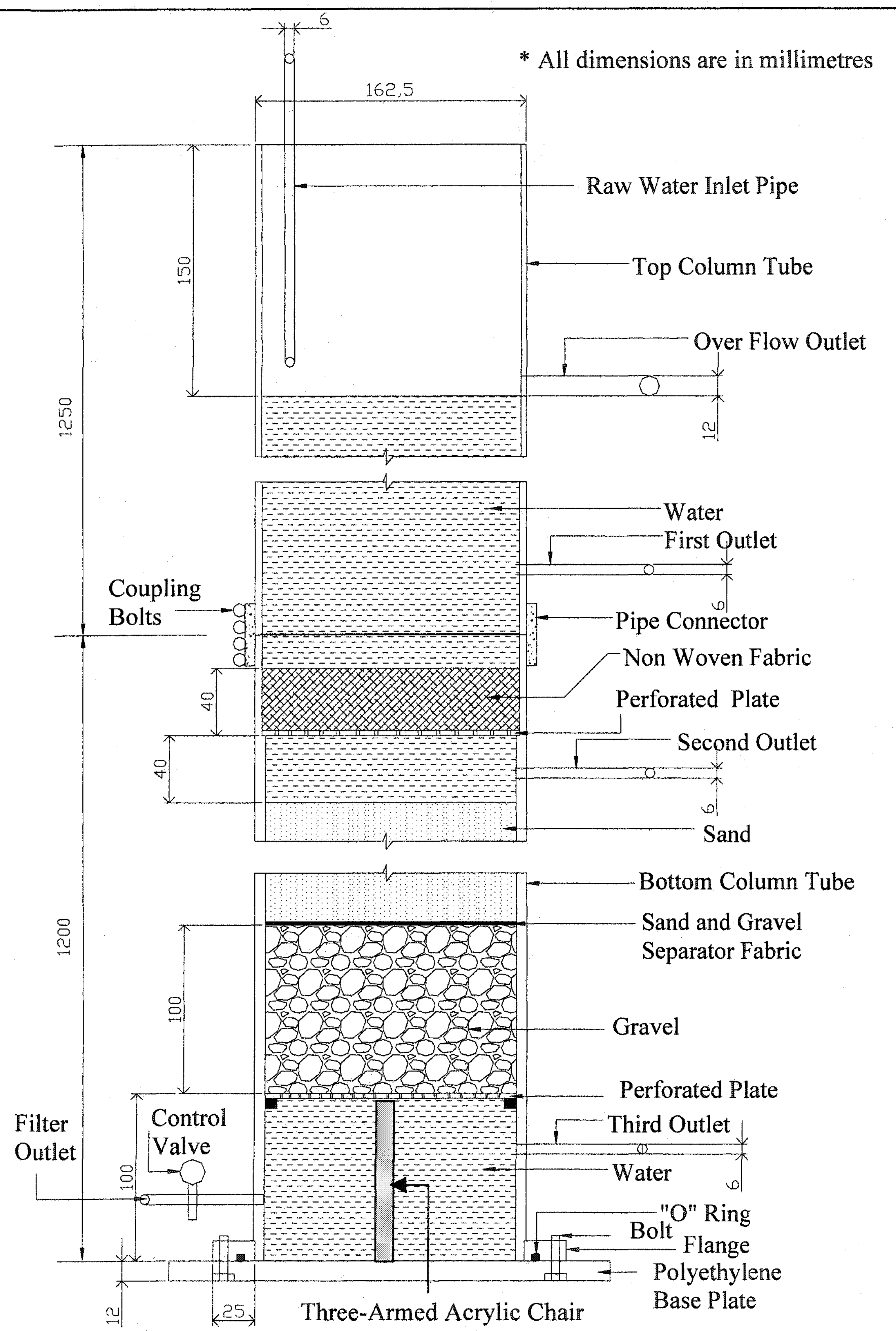



**Figure 3.3:** Detail Drawing of Filter Column

The steel base had four 2.5 m long steel stands which formed the frame to support all the top parts of filter columns using a wooden holder attached to the frame. The frame also supported a 1.75 m X 1.2 m wooden board at the backside. This board contained all the 1.4 m long 3 mm ID acrylic piezometer tubes and all the sampling ports. The filters with fabric on sand bed had three outlets for sampling and head measurement. The top outlet was situated at 100 mm above the top surface of fabric, second outlet was at 20 mm below bottom surface of fabric, and the third outlet was situated at the underdrain system. Filter 1 had only two outlets, the first outlet and third outlet. All these outlets were connected to the piezometers and sampling ports on the wooden board using 6 mm ID vinyl tubing. There was a gap of 40 mm between the bottom surface of fabric and top surface of sand bed for sample collection without disturbing filter media.

The fabric layers were supported by a stainless steel strainer (58 % open area with 4 mm diameter perforation and 1 mm thickness) which sat on a continuous support attached to the column wall. A rubber O-ring was provided on top of fabric layers to protect the water flow along the wall. An 8 mm wide PVC strip was placed on top of rubber O-ring to keep the fabric layers in position against buoyancy. All the filter units had the final filtrate outlets through the underdrain system. These outlets had filtration rate control valves, and were connected to 6 mm ID vinyl tubes which were raised to the level of 50 mm above the top filter media surface. These tubes drained the filtrate into an open-top polyethylene funnels which allowed the filtrate to flow into a 150 L filtrate collection tank. The high elevation of the filtrate outlets was maintained to avoid any negative pressure development within the filter media. The top parts of the filter columns had influent overflow outlets keeping 150 mm freeboard on top. These overflow outlets were connected to a 450 L filter overflow tank using 12 mm ID vinyl tubing. For the filter inlets 6 mm ID vinyl tubes were used. These tubes were connected to the distribution manifold and to the flow control valves controlling the inflow to the filters. The filter underdrain system consisted of 100 thick gravel layer supported by a metal strainer. The strainer sat on a 100 mm high three-armed chair made of 8 mm thick acrylic plate. Thus, the chair transferred all the loads coming from 0.9 m sand bed and 0.1 m gravel layer to the filter base plate.

### 3.4.3 Filter Operation

The filters were operated continuously from the start to the end of the filter run time. Simulated raw water was prepared in the laboratory in the mixing tank. Different compounds were added to aged tap water in the mixing tank, and mixed with a stirrer. The mixed water was then transferred to the feed tank. The stirrer in the feed tank was controlled by an electric timer which turned on the stirrer for 30 minutes in every two hours. The stirrer speed in the feed tank was 200 rpm. The water flow rate from the feed tank to the filters was controlled by the valves in distribution manifold. As water level in the feed tank went down, the flow rate decreased for a specific valve opening. Thus the valves were adjusted thrice a day to maintain the required influent flow rate to the filters. The influent flow rate to the filter was kept a bit higher than the required filtration rate. The excess influent water was collected in the filter overflow tank by using the filter overflow outlet. This arrangement maintained a constant water column height above the filter media. The raw water collected in the overflow tank was transferred to the feed tank twice a day. The filtration rate in the filter column was controlled by the filter outlet valve. The filtration rate decreased with time due to the head loss development in the filter. Thus, the filter outlet valve was adjusted every day to maintain constant filtration rate. The filtrate was collected in the filtrate tank and drained there after.

After initial installation of the filter columns, they were filled with clean dechlorinated tap water using the bottom filter outlets to avoid entrapped air in the filter media. When the water level was 0.2 m above the top surface of the media, the back flow was stopped and filter inlet carrying the raw water was opened and the columns were filled to the filter overflow outlet level. When all the filter columns were ready, the filtration was started by opening the filter outlet valves. At the end of the filter run, the filtration was stopped and water in the columns were drained to the level of the top surface of the filter media. The top part of the column was removed by opening the mid junction of the column for the cleaning operation of the filters. After cleaning, the top column part was reinstalled and the subsequent filter run was initiated.

***Water Sampling:*** Water samples were collected every day from different sampling ports for different water quality parameters analyses. For each sample, 300 mL of water was collected and used for all the testing. Filter overflow outlet was used for filter influent water sample. Filtrates were collected from sampling ports after the fabric layers and after the sand bed. During the sampling from the ports after the fabric layers, the final filter outlet valves were closed and the sampling ports after fabric layers were opened for about 15 minutes. During this time the water was only flowing through the fabric layers and there was no flow through the sand bed. This was done to avoid higher filtration velocities through the fabric layers during sampling. All samples were analysed immediately. Samples, which required storage, were preserved according to the *Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA and WEF 1998).

### 3.5 Materials for Raw Water Preparation

Bentonite clay, mix algae culture, glucose and settled wastewater primary treatment effluent were mixed with pre-treated tap water to simulate the raw water for selected ranges of the water quality parameters.

#### 3.5.1 Bentonite Clay

Bentonite clay was used to provide the suspended particles in the raw water. These suspended particles contributed to the turbidity of the raw water. Bentonite clay (B3378, CAS 1302-78-9) was obtained from Sigma Chemical Company, U. S. A. Maximum Particle size of this clay was 74 μm, 90 % passing size was 7 μm, and 10 % passing size was 2.7 μm. Suspensions of different concentration were prepared and measured for the turbidity and the relationship is shown in Appendix C. The concentration value of bentonite clay suspension corresponding to the target turbidity was used for the raw water preparation.

### 3.5.2 Algae Culture

As the SSF are expected to treat surface water, the surface fresh water algae were deemed to be appropriate for the experiments. Algae culture was used to provide different types of algae population in the raw water. The cultures were collected from two different sources. One was collected from a local pond and cultured in the laboratory. The details of algae culturing are explained in Appendix D. The types of algae present in this culture were not determined but it was expected that several types of surface fresh water algae were present. Two algae cultures were also collected from Carolina Biological Supply, U. S. A. One was culture of *Euglena* (Unicellular Flagellate, CAT DN-15-1351), and the other was mixture of five representatives of green algae (CAT DN-19-9980). The types of algae present were *Chlorella*, *Scenedesmus*, *Selenastrum*, *Ulothrix* and *Volvox*. These cultures were grown in the laboratory using Alga-Gro Freshwater Medium (CAT 15-3752) from Carolina Biological Supply. It is a universal media for freshwater algae. The culture media was buffered at pH 7.8 and rapidly produce dense cultures. Once the primary cultures were grown, all three cultures (mix culture from the local pond, *Euglena* and Green Algae Mixture) were mixed in equal ratios in a big culture vessel and were grown for the use in simulated raw water.

### 3.5.3 Treated Wastewater Effluent

Settled wastewater, which received primary treatment, was used to provide the bacteria population, several other organisms, and organic and inorganic compounds as the nutrient source in the raw water for the growth of biological population in the filter. About 20 L treated wastewater effluent was collected every week from Lou Romano Wastewater Reclamation Plant, Windsor. The effluent was kept in a refrigerator at 4°C temperature. The samples were collected before the final disinfection (chlorination in this case) of the effluent. Table 3.4 shows the characteristics of the collected wastewater treatment effluent.

**Table 3.4:** Characteristics of Treated Wastewater Effluent

| **Parameters** | **Average Value** | **Range** |
|---|---|---|
| Total Organic Carbon (TOC), (mg/L) | 32.7 (n = 14) | 28.4-36.5 |
| Total Coliform, (CFU/100 mL) | 1418600 (n =14) | 547000-2800000 |
| *E. coli*, (CFU/100 mL) | 214100 (n =11) | 74800-733000 |
| Ammonia-Nitrogen, (mg/L) | 47.3 (n = 11) | 36.8-57.5 |

* n – Number of Samples

### 3.6 Experimental Phases

The experiments were carried out in three different phases at room temperature. The details are given in Table 3.5.

**Table 3.5** Experiment Phases and Experimental Conditions

| **Experiment Phases** | **Objectives** | **Experimental Conditions** | **Important Parameters** |
|---|---|---|---|
| **Phase I** | To study the hydraulic behaviour of SSF aided with NWF and head loss development with influent of high turbidity | - High Turbidity (9 to 12 NTU)<br>- Low TOC (<1 mg/L) | Head loss and Turbidity |
| **Phase II** | To study the development of biological layer, and its effect on treated water quality with influent of low turbidity and high TOC | - Low Turbidity (1 to 2 NTU)<br>- High TOC (4 to 9 mg/L)<br>- High level of coliform Bacteria (2,000 to 10,000 CFU/100 mL) | Head loss, Turbidity, Total coliform, *E. coli*, TOC, Nitrate, and Ammonia |
| **Phase III** | To study the ripening of filter and performance after filter cleaning by removing top fabric layer | - Same conditions as for the Phase II with the exception of removing the top layer of fabric at the end of filter run in Phase II | Head loss, Turbidity, Total coliform, *E. coli*, TOC, Nitrate, and Ammonia |

### 3.7 Simulated Raw Water Preparation

The steps followed to prepare simulated raw water are described below:

- Tap water was stored in the mixing tank and was aerated with compressed air for more than 16 hours to remove residual chlorine.
- 1 to 4 L of settled primary treatment effluent was mixed in 400 L of stored water. The amount of wastewater treatment effluent mixed depended on its total coliform counts. The target total coliform count in the mixture was 1000-10,000 CFU/100 mL.
- Bentonite clay suspension was prepared by using 17 g Bentonite clay powder and then mixed to the tank water during Phase I. The target turbidity of the mixed water in this case was 9 to12 NTU.
- 300 to 500 mL of dense mix algae culture was added to the tank water to achieve Chlorophyll-A concentration of about 3 to 5 μg/L.
- 5 to 10 g of D-glucose (CAS 50-99-7) from Fisher Scientific Company was added to the tank water during part of Phase II, and Phase III experiments. Along with wastewater effluent and mix algae culture, it contributed 4 to 9 mg/L of final total organic carbon (TOC) in the raw water.
- After adding the above ingredients (as per the requirements of different experimental phases), the tank water was mixed using stirrer at 300 rpm for 20 minutes.
- The raw water was prepared everyday or once in two days. The excess from the previous batch was wasted.

The amount of different compounds mixed during different phases of the experiments and the related raw water quality parameters are shown in Appendix E.

Even though residual chlorine was not found in the aerated tap water by the residual chlorine presence/ absence (P/A) test using O-tolidine solution, this water was found to contain some unknown compounds toxic to the coliform. Survival tests were done for the coliform in raw water, and it was observed that coliform was dying within 8 hours of mixing (details are given in the Results and Discussion Chapter). After several different efforts, activated carbon (AC) filtered water was found to allow survival of the coliform in the raw water. Thus, from $36^{th}$ day to the end of Run 2, and entire operation period for Run 3, an AC (Advantage VIII home water system from Challenger Filtration Ltd., Canada) was used for treatment of the laboratory tap water. The system contained coconut-based granular activated carbon (GAC, Model-CC20) in two, 500 mm long PVC cartridge housing. It was an up flow cartridge and adsorbed residual chlorine and others compounds (unknown) from the tap water. The flow rate was kept as low as 1 L/min for better adsorption of contaminants.

### 3.8 Operational and Monitoring Parameters

Table 3.6 shows the parameters monitored and the frequency of analysis.

**Table 3.6:** Parameters and Frequency of Analysis

| **Parameters** | **Frequency** |
|---|---|
| Head Loss | Twice a Day |
| Turbidity | Daily |
| Feed Water Temperature | Daily |
| Feed Water Dissolve Oxygen | Daily |
| Feed Water Chlorophyll-A | Twice a Week |
| PH | Daily |
| Nitrate | Thrice a week |
| Ammonia | Thrice a week |
| Total Organic carbon (TOC) | Four Times a Week |
| TC & *E. coli* | Twice a Week |

### 3.9 Analytical Methods

*Standard Methods for the Examination of Water and Wastewater* (APHA, AWWA and WEF 1998) was followed for all the above analyses except head loss and residual chlorine measurements.

### 3.9.1 Turbidity

Standard Methods 2130-Nephelometric method was followed for the turbidity measurement by using Hach Ratio/XR Turbidimeter (Model 43900). This instrument has four different scales (0 to 2 NTU, 0 to 20 NTU, 0 to 200 NTU, and 0 to 2000 NTU) for turbidity measurements. The accuracy of this meter is ± 2 % of the full scale. Calibration of the meter was done according to the instruction manual of the instrument. All the samples were degassed by applying vacuum. Samples were duplicated and the average values are reported. Turbidity readings are reported to the nearest 0.05 NTU for the turbidity range of 0 to 1.0 NTU, to the nearest 0.1 NTU for the turbidity range of 1 to 10 NTU, and to the nearest 1 NTU for the turbidity range of 10 to 40 NTU.

### 3.9.2 pH

The pH of the samples was measured according to the Standard Method 4500 Electrometric Method using Orion Research Expandable Ion Analyzer (Model EA940). Orion pH electrode (Model 9107 BN), included with ATC probe (temperature compensating device), was used with the ion analyzer. The precision and accuracy of the pH measurements were 0.001 and ± 0.005, respectively. The instrument was calibrated using two points calibration bracketing the expected pH before measuring a set of samples. Samples were measured at room temperature with gentle stirring to ensure the sample was homogenous. The results are reported to the nearest 0.01 pH unit.

### 3.9.3 Chlorophyll-A

Concentration of photosynthetic pigment was used to estimate phytoplankton biomass. All green plants contain Chlorophyll A, which constitutes approximately 1 to 2% of dry mass of planktonic algae. Standard Method 10200 H Chlorophyll (Spectrophotometric Method) was followed for the Chlorophyll A measurement. All the samples were filtered immediately after sampling through glass fibre filter (Whatman GF/F-0.7μm). Kontes Glass tissue grinder (Glass/TFE grinder, Model 886000) and Teflon headed pestle were used for grinding the cells using 90% aqueous acetone solution. Samples were macerated at 500 rpm for 1 minute. The extract was separated using IEC Centra-8 Centrifuge running at 500 G for 20 minutes. Clarified extract was decanted in clean, calibrated, 15 mL, screw-cap centrifuge tube and total volume was measured. For spectrophotometer, 1-cm path length glass cuvettes were used. Using 3 mL clarified extract, optical density (OD) was measured at 750 nm and 664 nm wavelengths using Varian-CARY 50 Scan, UV-Visible Spectrophotometer. The samples were then acidified with 0.1 mL of 0.1 N HCl. After 90 seconds, OD were measured again at 750 nm and 665 nm wavelengths. The 750 nm OD values were subtracted from the OD readings of before (OD at 664 nm) and after acidification (OD at 665 nm). Using the corrected values, Chlorophyll-A was calculated as shown below:

$$\text{Chlorophyll-A, (mg/m}^3\text{ or }\mu\text{g/L)} = \frac{26.7(664_b - 665_a)V_1}{V_2 L_1} \ldots\ldots\ldots\ldots\ldots (3.1)$$

Where, $V_1$ = Volume of extract, (L)

$V_2$ = Volume of sample, ($m^3$)

$L_1$ = Light path length or width of cuvette, (cm)

$664_b$, = Optical densities of extract before acidification, and

$665_a$ = Optical densities of extract after acidification.

The value 26.7 is the absorbance correction.

### 3.9.4 Dissolve Oxygen

Dissolved oxygen (DO) was measured by using YSI 85 Oxygen meter according to the Standard Method 4500-O G- Membrane Electrode method. YSI 85 Oxygen meter has the resolution and accuracy of 0.01 mg DO/L and ± 0.3 mg DO/L, respectively. The instrument was calibrated each time it was turned on by following the instructions in the manual. DO was only measured for the water in mixing tank and feed tank. During sample measurement, the electrode was moved with vertical motion to overcome erratic response. The readings were recorded when became stable. The readings are reported to the nearest 0.01 mg /L of DO.

### 3.9.5 Total Organic Carbon

Total Organic Carbon (TOC) was measured according to the Standard Method 5310 B High-temperature Combustion method. Shimadzu TOC-VSH Carbon Analyzer was used for the TOC measurements. The detection limits of this analyzer are 50 μg/L for total carbon (TC) and 4 μg/L for inorganic carbon (IC). The reproducibility of measurements of this instrument is within ± 1.5 %. Calibration curves for TC and IC were prepared by using multi point calibration method. 1000 mg-C/L of total carbon stock was prepared by using $KH_2PO_4$ and 1000 mg-C/L of inorganic carbon stock was prepared by using $Na_2CO_3$ and $NaHCO_3$. For each batch of analysis at least one secondary standard (prepared from stock standard) was checked with the prepared standard calibration. The readings were averaged for three injections values. The IC values were deducted from the TC values to get TOC values for the samples. A magnetic stirrer was used to keep the sample homogeneous during the measurements. The readings are reported to the nearest 0.01 mg /L of TOC.

### 3.9.6 Nitrate

Standard Method 4500 $NO_3^-$ D Nitrate Electrode method was followed for nitrate ion measurement. A half cell nitrate ion selective electrode, Orion Research Ion Selective Electrode, Model 93-07, was used with a double-junction reference electrode, Accumet Electrode, CAT 13-620-47, filled with 5.3 g/L $(NH_4)_2SO_4$ solution. Orion Research 290A ion analyzer was used for the concentration measurement. The accuracy of this ion analyzer is ± 0.05 % and the electrode has the minimum detection limit of 0.1 mg $NO_3^-$-N/L. The standards for calibration curves and interferences suppressor buffer solution were prepared according to the Standard Methods. For sample measurement, 20 mL of sample and 20 mL buffer solution were kept in 50 mL beaker and gently mixed with magnetic stirring bar. The millivolt reading was recorded when it had stabilized and concentration was found from the calibration curve. All the samples were duplicated and average values are reported to the nearest 0.1 mg $NO_3^-$-N/L.

### 3.9.7 Ammonia

Standard Method 4500-$NH_3$ D Ammonia-Selective Electrode Method was followed for ammonia measurement. An ammonia gas sensing electrode, Accumet CAT 13-620-504, was used. Orion Research 290A ion analyzer was used for the concentration measurement. The accuracy of this ion analyzer is ± 0.05 % and the electrode has the minimum detection limit of 0.01 mg $NH_3$-N/L. Calibration curve was obtained with the standards prepared from $NH_4Cl$. For the sample measurements 25 mL of sample was kept in 50 mL of beaker and mixed gently with magnetic stirring bar to avoid possible loss of ammonia from the solution. After immersing electrode in the sample, sufficient volume of 10 N NaOH solution (0.25 mL was usually sufficient) was added to raise pH above 11.0. The millivolt was recorded when the reading had stabilized. All the samples were analyzed in duplicate, and average values are reported to the nearest 0.01 mg $NH_3$-N/L.

### 3.9.8 Total Coliform and Fecal Coliform

***Total coliform***: Standard Method 9222 B Standard Total Coliform Membrane Filter Procedure was followed for total coliform enumeration. Grided membrane filters (Millipore HAWG047S3- S-Pak sterile membrane filters) of 0.45 μm pore size and 47 mm diameter were used for filtration of the samples. m-Endo Total Coliform Broth (Millipore MB000000E) was used for the media. The petri dishes containing the filters were incubated in a dry type Bacteriological Incubator (Blue-M) at temperature 35 ± 0.5 °C for 24 hours. For each sample, 2 to 3 different dilutions were prepared and red colonies with a golden metallic sheen were counted within the standard count range (ideal colony number is 20 to 80 per plate and not more than 200) and are reported as CFU/100 mL.

***Fecal coliform***: Standard Method 9222 D Fecal Coliform Membrane Filter procedure was followed for fecal coliform enumeration. Grided membrane filters (Millipore HAWG047S3- S-Pak sterile membrane filters) of 0.45 μm pore size and 47 mm diameter were used for filtration of the samples. m-FC Fecal Coliform Broth (Millipore

MB000000F) was used for the growth media. The petri dishes containing the filters were placed in a waterproof plastic bag, inverted, and submerged in water bath for incubation at temperature 44.5 ± 0.2 °C for 24 hours. For each sample, 2 to 3 different dilutions were prepared and colonies with various shades of blue (standard count range is 20 to 60 fecal coliform colonies) were counted and are reported as CFU/100 mL.

The growth media for both the total coliform and fecal coliform tests were prepared in the laboratory (see Appendix F for detail growth media preparation). This membrane filtration technique of total coliform and fecal coliform enumeration was used during the filter Run 1.

### 3.9.9 Total Coliform and *E. coli*

In addition to MF technique, total coliform was also enumerated by using IDEXX Quanti-Tray MPN Method. *E. coli* could be measured in the same test. Quanti-tray/2000 and Colilert Test Kit (CAT WP020) from IDEXX Laboratories, Inc., U. S. A. were used in this method. This method of total coliform and *E. coli* enumeration was used during the filter Run 2 and Run 3.

***Colilert Test Kit:*** This test kit simultaneously detects total coliform and *E. coli* in water based on IDEXX's patented Defined Substrate Technology (DST). When total coliform metabolize Colilert's nutrient-indicator, the sample turns yellow. The sample fluoresces when *E. coli* metabolizes Colilert's nutrient-indicator. Colilert can simultaneously detect these bacteria at 1 CFU/100 mL within 24 hours even with as many as 2 million heterotropic bacteria per 100 mL present.

***Quanti-tray/2000:*** IDEXX Quanti-Tray/2000 is designed to give quantitated bacterial counts of 100 mL samples using IDEXX Defined Substrate Technology reagent products. This tray can measure total coliform or *E. coli* up to 2000 CFU/100 mL of sample. The samples, that contained coliform or *E. coli* more than 2000 CFU/100 mL, were diluted accordingly with sterile water.

*Test Procedures:*

- Contents of one Colilert snap pack were added to a 100 mL water sample in a sterile vessel.
- The vessel was caped and shaken until the powder dissolved.
- The sample and reagent mixture were poured directly into the Quanti-Tray avoiding inside contact.
- Sample filled Quanti-Tray was placed onto the Quanti-Tray/2000 rubber insert of the Quanti-Tray Sealer (Model 2X, IDEXX Laboratories, Inc.) with the well side of the tray facing down.
- The Quanti-Tray was sealed by inserting the tray into the sealer.
- The tray was incubated at 35 ± 0.5 °C for 24 hours in a dry type Bacteriological Incubator (Model Blue-M).
- The number of big and small positive wells for total coliform and *E. coli* was determined by using the result interpretation table (Table 3.7).

**Table 3.7:** Quanti-Tray Result Interpretation

| Appearance | Result |
|---|---|
| Less yellow than the comparator | Negative for total coliform or *E. coli* |
| Yellow equal to or greater than the comparator | Positive for total coliform |
| Yellow and fluorescence equal to or greater than the comparator | Positive for *E. coli* |

- A 6-watt, 365 nm, UV lamp was used for the fluorescence by keeping the lamp within 125 mm from the tray, in a dark environment.
- MPN chart (Appendix G) provided by the manufacturer was used to find the corresponding coliform or *E. coli* count.

The results are reported as CFU/100 mL.

### 3.9.10 Head Loss

Head loss was measured by using acrylic clear tube piezometer of 3 mm ID and 1.4 m length. Reference point for each piezometer was marked by using levelling instrument. The capillary action was minimized when the water head in any piezometer was deducted from the head in the reference piezometer. The readings are reported to the nearest 1 mm.

### 3.9.11 Residual Chlorine

O-tolidine solution was used to test the presence/absence of residual chlorine in the stored tap water and AC filtered tap water. This test was done according to the procedure described in a report published from New York State Food Laboratory (Oglesby et al. 2002). The solution was prepared by dissolving 0.135 g of O-tolidine (3, 3' – dimethyl bencidine) in a mixture of 85 mL deionized water and 15 mL concentrated HCl and the solution was stored in amber bottle. The test was done by adding 0.25 mL of O-tolidine solution to the 10 mL sample. Appearance of a yellow colour after gentle shaking for 30 seconds indicated the presence of residual chlorine in the sample.

# Chapter IV

# RESULTS AND DISCUSSION

## 4.1 General

This chapter presents the results obtained in this study and the pertinent discussions. The results and discussions are presented according to the different phases of the experiments. At the end of this chapter, effects of selected parameters on the filter performance are summarized.

## 4.2 Phase I

This phase of the experiments was started with unused sand and NWF. All filters were operated for 20 days, after which the required flow rate of 0.1 m/h could not be maintained for most of the filters. The filer operation in this phase is named Run 1.

### 4.2.1 Influent Water Characteristics

The simulated influent water was prepared by using tap water, as described in Section 3.7. Tap water in the mixing tank was dechlorinated by aerating for more than 16 hours before adding the other ingredients. The dechlorination was confirmed by O-tolidine chlorine presence/absence test. A summary of the simulated raw water characteristics is shown in Table 4.1. The daily raw water characteristics for this filter run are shown in Appendix E (Table E.4).

**Table 4.1:** Raw Water Characteristics (Run 1)

| Parameters | Average ± SD* | Maximum | Minimum |
|---|---|---|---|
| Temperature, (°C) | 20.5 ± 1.1 | 22.3 | 18.4 |
| DO, (mg/L) | 8.76 ± 0.5 | 9.56 | 7.89 |
| pH | 7.43 ± 0.3 | 7.86 | 6.83 |
| Turbidity, (NTU) | 11 ± 0.9 | 12 | 9.2 |
| TOC, (mg/L) | 0.37 ± 0.1 | 0.67 | 0.22 |
| Chlorophyll- A, (μg/L) | 2.98 ± 0.8 | 4.2 | 1.5 |

* Based on 21 samples collected over a period of 20 days; SD-Standard deviation

From Table 4.1 it is seen that the raw water turbidity ranged between 9 to 12 NTU, which was about twice the maximum recommended value of 5 NTU of direct filtration using SSF (Cleasby 1991). This turbidity was mostly due to the bentonite clay. When the treated wastewater effluent and algae culture were mixed (before the clay was mixed) in the raw water, the turbidity was within the range of 1.2 to 2 NTU (n = 10). Settling of some of the added bentonite clay in the feed tank was avoided by running a stirrer in the feed tank for 30 minutes in every 2 hours. The TOC of raw water was low (0.22 to 0.67 mg/L, average = 0.37 mg/L), and was contributed by the wastewater effluent and algae culture. Average chlorophyll-A content of 2.98 μg/L in the raw water was within the recommended amount (< 5 μg/L) of chlorophyll-A for the SSF raw water (Cleasby 1991). Since the chlorophyll-A represents about 1.5 % of the dry mass of planktonic biomass (APHA, AWWA and WEF 1998), the daily average planktonic biomass concentration in the feed water was estimated to be 0.20 mg/L.

Microorganisms, algae, trace levels of organic matter, and nutrients are typically present in all surface water sources. As the presence of microorganisms and their growth and activity in SSF contribute to enhanced water treatment as compared to the rapid sand filter, treated wastewater effluent was added to simulated raw water as source of microorganisms, organics and nutrients. A mixture of algae culture was also added to simulate the presence of algae in surface waters. As a batch of simulated raw water was used over 24 hours, a survival study of microorganisms using coliform group of bacteria as indicator was done after mixing the treated wastewater effluent. The results are presented in Table 4.2. Contrary to expectation, the test revealed that after 8 hours no coliform was detected in the raw water, even though the presence of chlorine in the stored and aerated water could not be detected by O-tolidine test for chlorine presence/absence. However, some growth of non-coliform group of microorganisms was observed in the test plates. This indicated the presence of some toxicity (to biological activity) by unknown compounds in the tap water. As the residence time of the water in the supernatant feed water reservoir was 11 hours, the population of microorganisms reaching the filter bed was expected to be much lower than that in the simulated raw water at the time of its preparation.

**Table 4.2:** Total Coliform and Fecal Coliform in Raw Water at Different Times after Preparation

| Time (Hours) | Total Coliform (CFU/100 mL) | | Fecal Coliform (CFU/100 mL) | |
|---|---|---|---|---|
| | Average | Range | Average | Range |
| 0 | 4000 | 4700-3500 | 580 | 620-530 |
| 3 | 600 | 670-520 | 110 | 130-80 |
| 6 | 80 | 90-60 | <1 | - |
| 8 | <1 | - | <1 | - |

* Based on tests done on three different days.

### 4.2.2 Clean Bed Head Loss

After installation of all the filters, the initial clean bed head losses were measured by using clean tap water with turbidity less than 0.1 NTU. These initial clean bed head losses were used as the references for the clean bed head losses in the subsequent filter runs, and to confirm the proper cleaning of filter at the end of each filter run. Table 4.3 shows the clean bed head losses at the filtration rate of 0.1 m/h.

**Table 4.3:** Clean Bed Head Losses before Run 1 at Filtration Rate of 0.1 m/h
(Head Loss Unit - mm)

| | **Filter 1** (0.9 m Sand Bed + 0 mm thick fabric) | **Filter 2** (0.9 m Sand Bed + 8.9 mm thick fabric) | **Filter 3** (0.9 m Sand Bed + 22.3 mm thick fabric) | **Filter 4** (0.9 m Sand Bed + 44.5 mm thick fabric) |
|---|---|---|---|---|
| **Fabric** | - | ND* | ND | ND |
| **Sand Bed** | 22 | 22 | 21 | 23 |
| **Total** | 22 | 22 | 21 | 24 |

* ND- Not detected

*Theoretical Clean Bed Head Loss:* The head loss of clean sand bed can be estimated by using the formulae proposed by Huisman and Wood (1974).

$$H = \frac{v_f}{k} . t \quad \text{......(4.1)}$$

$$k = 150(0.72 + 0.028T)\frac{p^3}{(1-p)^2}\varphi^2 d_s^2 \quad \text{......(4.2)}$$

$$d_s = d_{10}(1 + 2\log U) \quad \text{...(For U < 2)......(4.3)}$$

where,

k = Coefficient of permeability of the sand bed, (m/h)

T = Temperature, (°C)

p = Porosity of sand bed

φ = Shape factor

$d_s$ = Specific diameter of sand grains, (mm)

$d_{10}$ = 10% passing size of the sieve, (mm)

U = Uniformity coefficient ($d_{60}/d_{10}$)

H = Head loss in the sand bed (m)

$v_f$ = Filtration rate, (m/h), and

t = Thickness of the sand bed, (m).

For the present study, the parameters were: T = 21 $^0$C (during clean bed head loss test), $v_f$ = 0.1 m/h, U = 1.8, $d_{10}$ = 0.28 mm, t = 0.9 m, p = 0.38 (assumed), and $\varphi^2$ = 0.9 (assumed, for nearly spherical grains). From the Equations (4.1), (4.2) and (4.3), the values of k and H were estimated as 4.5 m/h and 0.02m (20 mm), respectively. The experimental clean sand bed head losses (Table 4.2) for all filters agree with this value.

### 4.2.3 Head Loss Development

The head loss measurements were taken at least twice daily, and only the average daily values are reported here. Figures 4.1 to 4.6 show the head loss development during the filter Run 1 in all the filters.

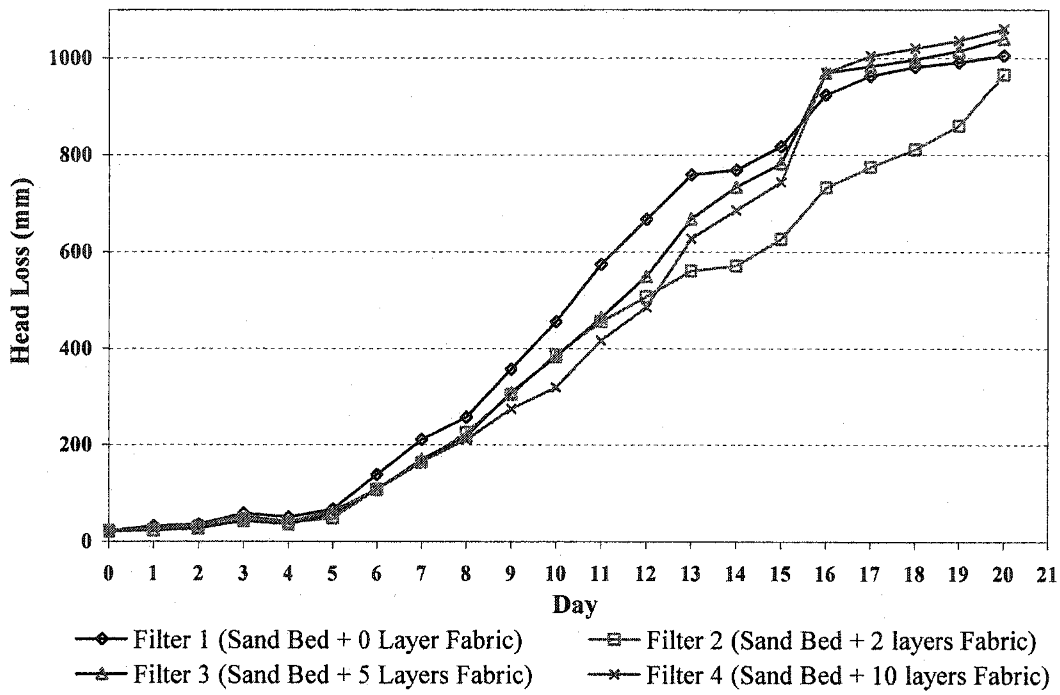



**Figure 4.1:** Comparison of Total Head Losses (Run 1)

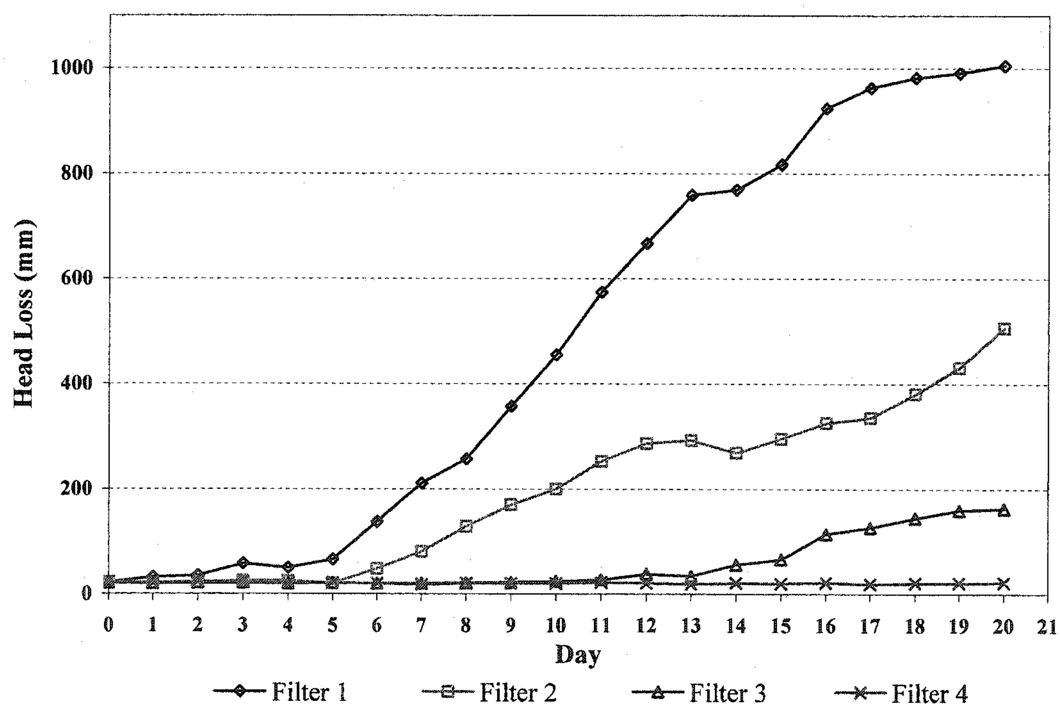



**Figure 4.2:** Comparison of Head Losses Across Sand Beds (Run 1)

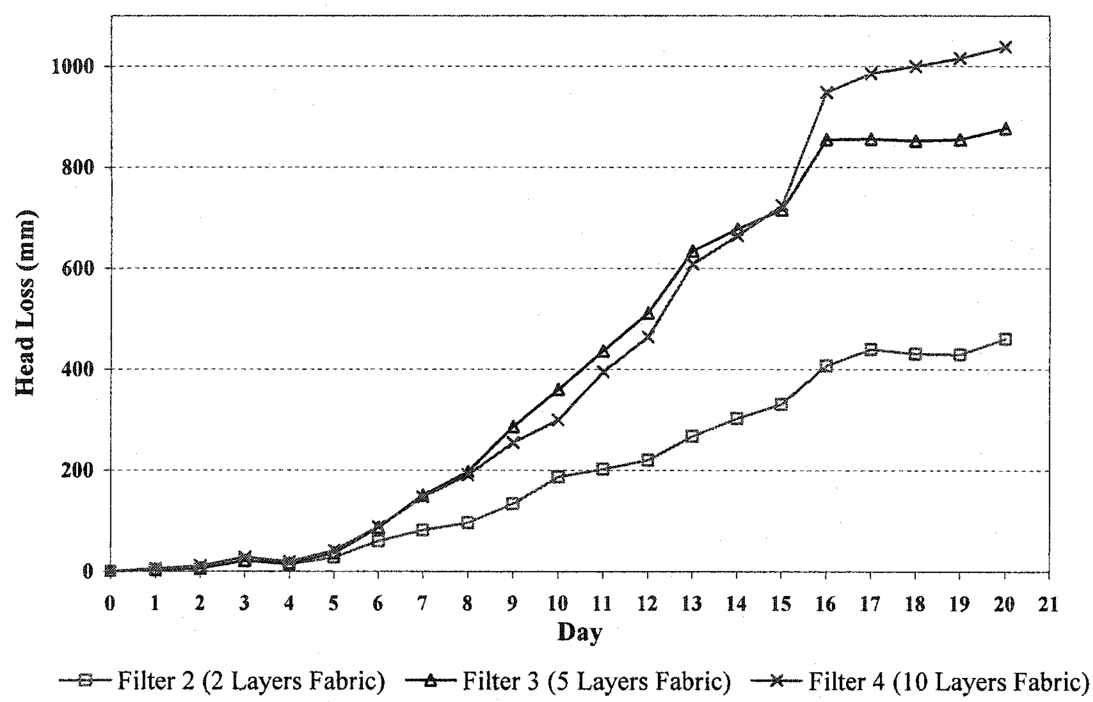



**Figure 4.3:** Comparison of Head Losses Across Fabric (Run 1)

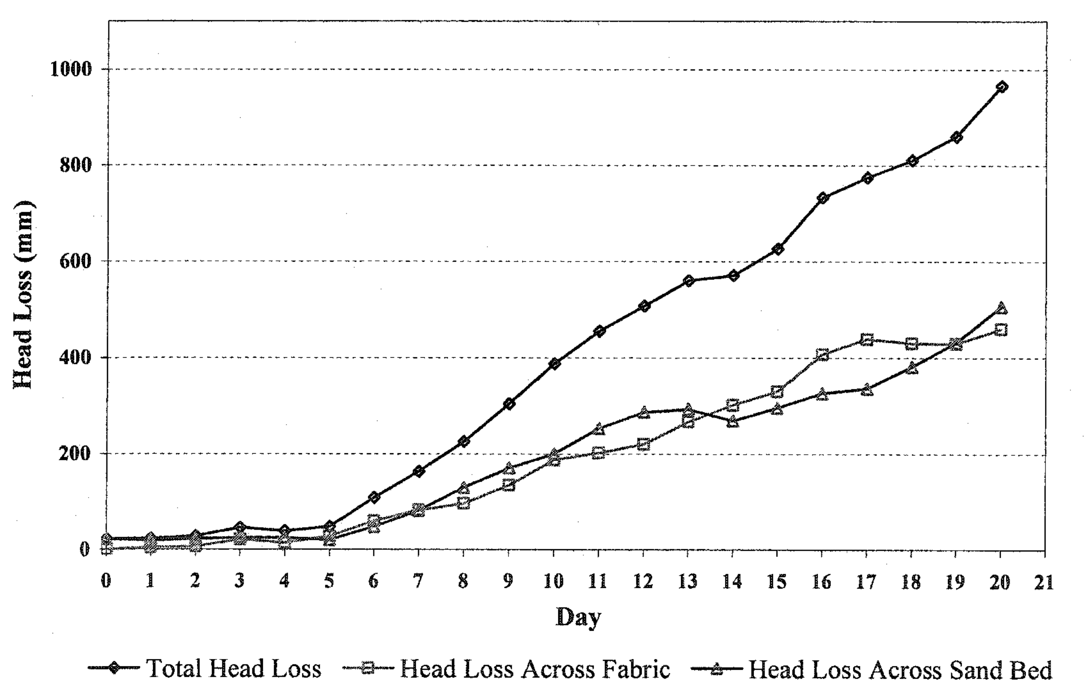



**Figure 4.4:** Head Losses in Filter 2 (Run 1)

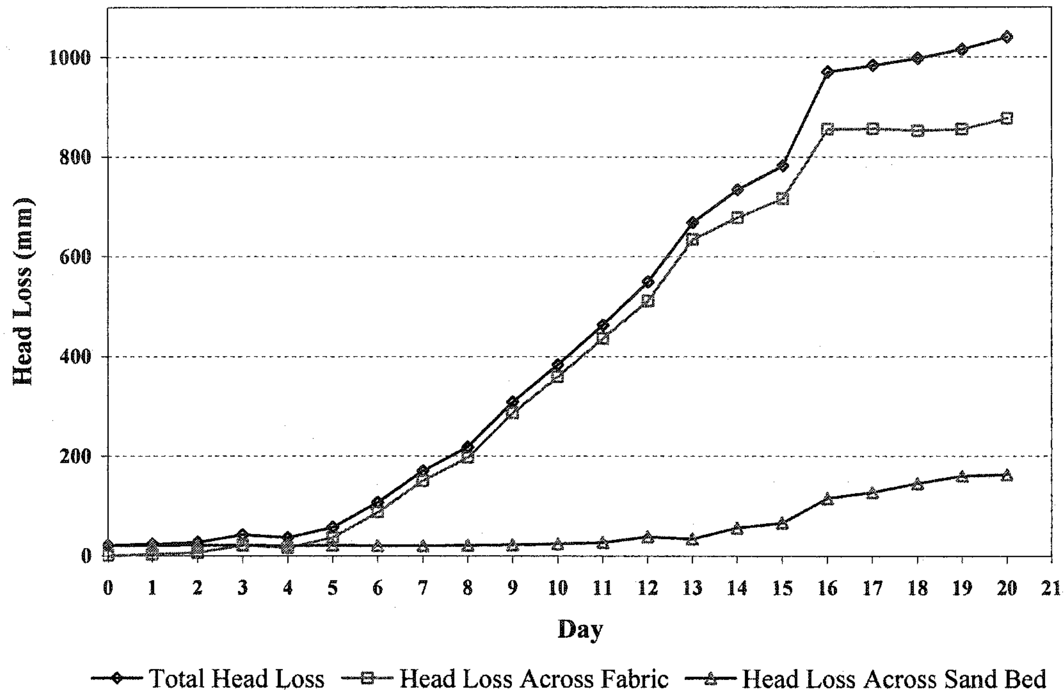



**Figure 4.5:** Head Losses in Filter 3 (Run 1)

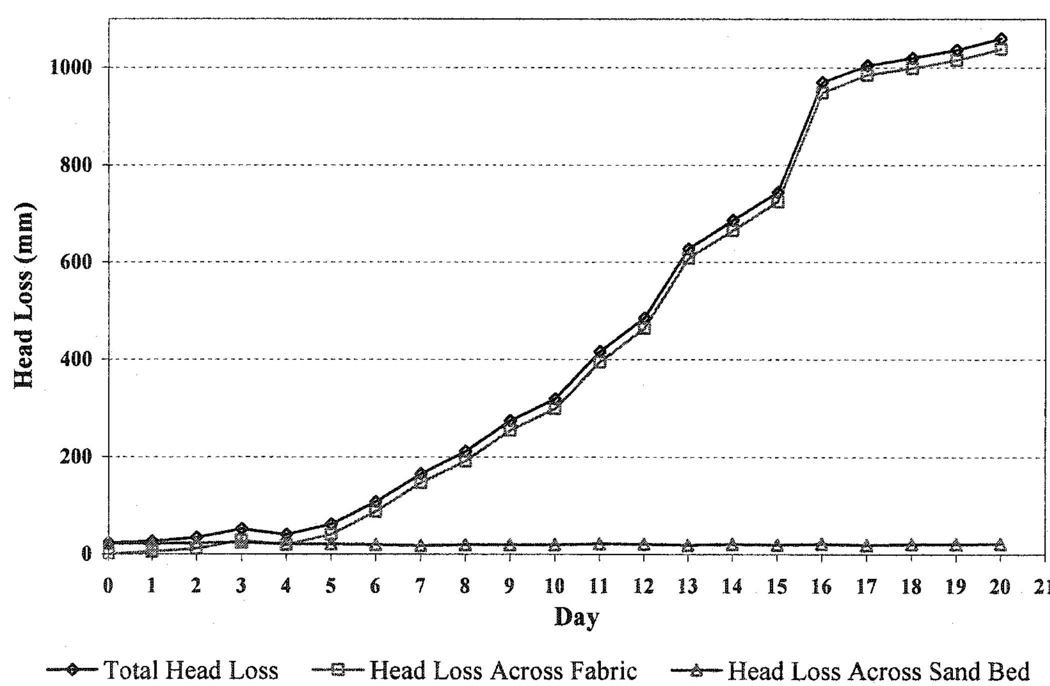



**Figure 4.6:** Head Losses in Filter 4 (Run 1)

Figure 4.1 shows the total head losses in different filters. For the first 5 days of filter operation, head losses in all the filters were less than 70 mm. After Day 5, head losses started to increase rapidly with the highest rate of increase in Filter 1 and lowest in Filter 4. The increment rates in Filters 2 and 3 were almost the same.

For all the filters, the 20 days filter operation time can be divided in to 3 stages (Stage 1: Day 0 to Day 5, Stage 2: Day 5 to Day 16, and Stage 3: Day 16 to Day 20). In Stage 1, the total head loss increment rates were low and uniform at 8 mm/d in all the filters. In Stage 2, the increment rates increased significantly to 78 mm/d for Filter 1, 62 mm/d for Filter 2, and 82 mm/d for both Filters 3 and 4. In this stage, total head losses in all the filters were best fitted with the $2^{nd}$ order polynomials as shown in Figure 4.7. In Stage 3, the head loss increment rates were in the range of 18 to 22 mm/d for Filters 1, 3 and 4, and it was 60 mm/d for Filter 2. For Filter 2, Stage 3 head loss development pattern was similar to Stage 2. From the head loss curves in Figure 4.7, it is observed that, on $17^{th}$ day, head losses values had reached 1052 mm to 1054 mm, which were more than the maximum head loss of 1050 mm allowed by the setup. For the Filter 1, it would happen on the $18^{th}$ day. As a result, during Stage 3 the filtration rate became lower than the desired filtration rate of 0.1 m/h, and consequently the head loss increment rates became lower than those of Stage 2. If the design filtration rate was to be maintained, Filters 1, 3 and 4 should have been stopped on $17^{th}$ day. The reported lowest filtration rate for SSF is 0.06 m/h (AWWA 1991). Since the filtration rates in Stage 3 did not fall below 0.085 m/h, the filtration operation was continued after $17^{th}$ day till $20^{th}$ day.

It can be seen from the plots of head loss development that the head loss curves for different filters resemble the typical standard S-type head loss development curve, named and explained by Toms and Bayley (1988). They stated that this pattern was most frequently observed in winter when biological activities were low. In the present study, even though the temperature was high (average 20.5 $^{o}C$), the bioactivity was limited by the characteristics of raw water, as discussed in Section 4.2.1, which may explain the S-type head loss development patterns observed.

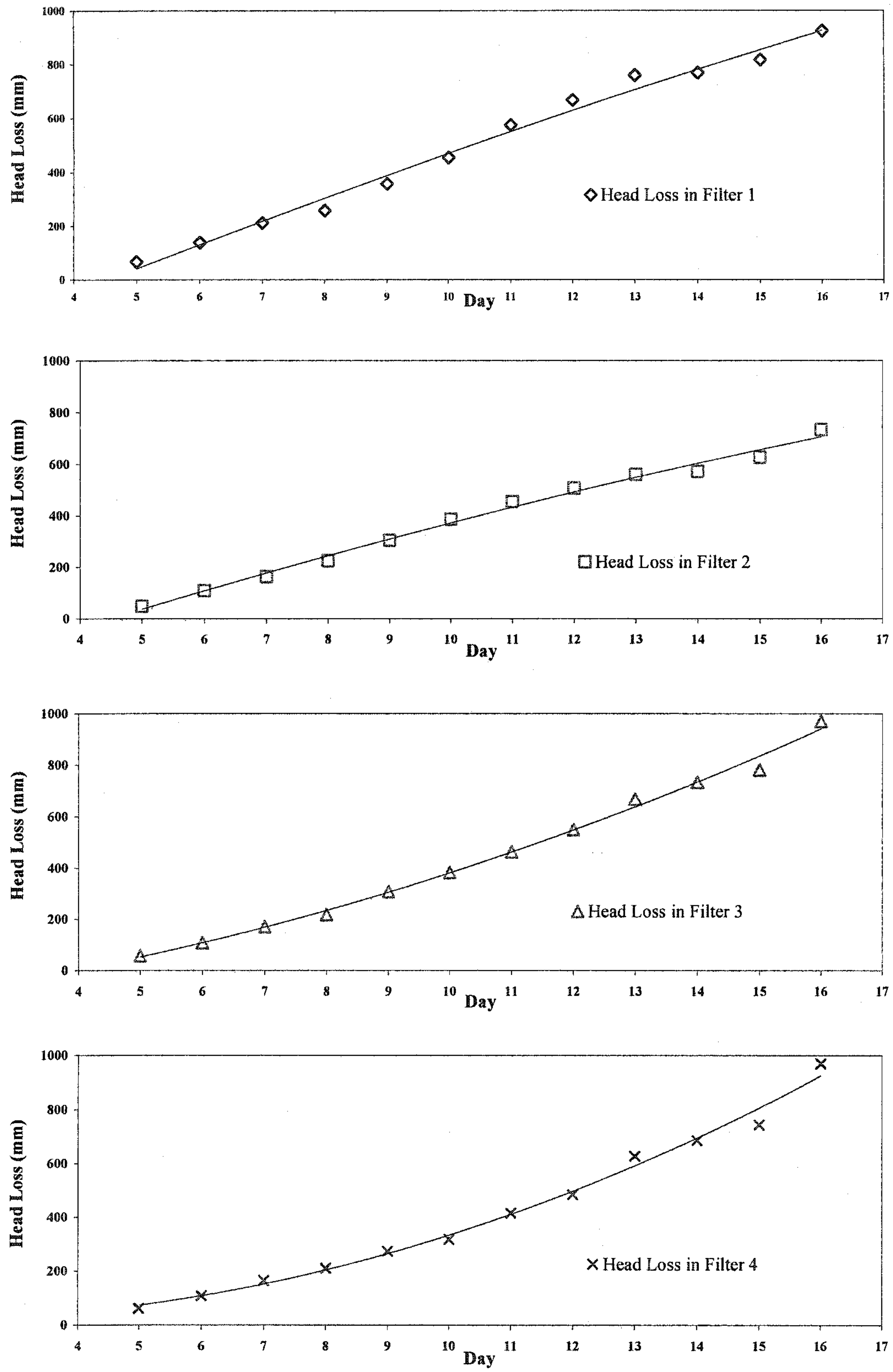



**Figure 4.7:** Trend Lines of Total Head Loss Development during Run 1 (Day 5 to Day 16)

Mbwette (1989) studied SSF with NWF and reported that filters with 6 (21.6 mm thickness), 4 (14.4 mm thickness), and 2 (7.2 mm thickness) layers of NWF (14, 430 $m^2/m^3$ fabric specific surface area), and filter without fabric produced head loss of 350 mm (maximum allowed) in 113 days, 111 days, 83 days, and 55 days, respectively, when operated at filtration rate of 0.15 m/h. This indicated that inclusion of fabric increased the filter operation time by a factor of 1.5 to 2. In the present study, all filters with different depths of fabric and the control filter reached the maximum head loss of about 1050 mm almost simultaneously. This indicates that inclusion of fabric, in this study, did not increase the filter operation time when compared to the control filter. Even if 350 mm of head loss was considered as the reference for the present study, the filter operation time increment would not be significant because increment factors varied from 1.1 to 1.16 in all filters with NWF. In the study by Mbwette, natural surface water of low turbidity, 1.1 to 4.4 NTU (average 2.3 NTU), was used. The size range of the solids present in this natural source of water is also expected to vary over a wide spectrum. In the present study, raw water turbidity was in the range of 9 to 12 NTU, and the size range of particles was 2.7 μm (10 % passing size) to 7 μm (90 % passing size). This may explain the difference in results of the present study and those of Mbwette's study.

Figure 4.2 shows the head losses in the sand beds. In Filter 1, there was no fabric and the total head losses were contributed by sand bed only. The head losses in sand beds started rising from Day 1 in Filter 1, Day 5 in Filter 2, and Day 11 in Filter 3. Sand bed in Filter 4 showed no measurable increase in head loss during the entire run of 20 days. The head loss in sand bed of Filer 3 reached to the maximum value of 160 mm on $20^{th}$ day. In Filter 2, the maximum value was 500 mm on $20^{th}$ day.

Figure 4.3 shows the head losses with varying thickness of fabric in different filters. During Day 0 to Day 5, there was no significant increment in head loss for all the filters. After Day 5, the head loss incremental increases were similar and higher in Filters 3 and 4 as compared to Filter 2. After Day 15, head losses in Filter 4 became higher than those of Filter 3. In case of Filter 2, head losses in fabric were low as compared to Filters 3 and 4. The maximum head loss in the fabric in Filter 2 was 460 mm on $20^{th}$ day.

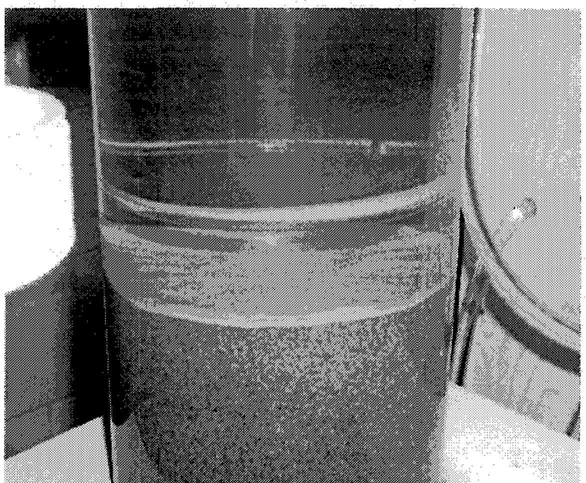
Figures 4.4, 4.5 and 4.6 show the total head losses, contributed by the sand beds and fabric layers of Filters 2, 3 and 4, respectively. In Filter 2, after Stage 1, the total head losses were almost equally contributed by fabric and sand bed (Figure 4.4). In case of Filter 3, during Stage 1 there was almost no head loss in the fabric, while during Stage 2 the head losses were mostly contributed by the fabrics, and the sand contributed only the clean bed head loss (Figure 4.5). In Stage 3, the sand bed started contributing to the head loss with the maximum head loss of 160 mm at the end of the filter run. Figure 4.6 shows that in Filter 4, after Stage 1, the total head loss development was entirely contributed by the fabric. Sand bed contributed only the clean bed head loss.

Filters 3 and 4 showed similar head loss development patterns as well as values, whereas, Filter 2 showed comparatively lower head loss increment rate, particularly after Day 11 of the filter operation. From Figure 4.4, it is found that the head loss across fabric in Filter 2 was increasing as in the other filters, but from Day 11 to Day 17 the head loss across sand bed was almost constant, which was anomalous to the behaviour of the sand beds in other filters where head losses were increasing. This anomalous behaviour of sand bed of Filter 2 between Day 11 and Day 17 remains unexplained.

### 4.2.4 Particle Deposition and Development of *Schmutzdecke*

Plates 4.1 a, b, and c show the particle deposition on sand surface in Filters 1, 2, and 3, respectively at the end of filter run. Plates 4.1 d, e, and f show the particle deposition on and within the fabric in Filters 2, 3, and 4, respectively at the same time.

In Filter 1, particles had deposited on the top surface and the next few millimetres of the sand bed, and at the end of 20$^{th}$ day about 3 mm thick layer of deposited particles was formed on the sand surface (Plate 4.1 a). This was confirmed when top 25 mm of sand was scraped at the end of the filter run and clean filter beds were checked for head losses. These measured head losses, about 22 mm in all filters, were similar to the clean bed head losses measured at the beginning of the run. In Filter 1, the layer had started to form on the sand surface after 2 to 3 days of filter operation, as indicated by the head loss values.

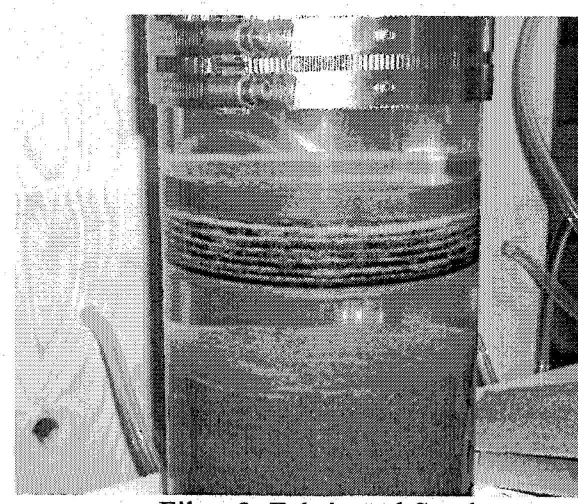


a. Filter 1: Sand Surface

b. Filter 2: Sand Surface

c. Filter 3: Sand Surface

d. Filter 2: Fabric and Sand



e. Filter 3: Fabric and Sand

f. Filter 4: Fabric and Sand

**Plate 4.1:** *Schmutzdecke* in Different Filters (Run 1)

In case of Filter 2, during Stage 1 of filter operation (Day 1 to Day 5) the particles were essentially deposited on and within the fabrics, and no deposition was noticed on the sand surface, which was also confirmed by the head loss data. During this period no head loss development was found in the sand bed. After that period, a thin grey layer of particles was observed on top of sand bed, along with the head loss development, which indicated that a significant portion of particles were escaping the fabric layer after Day 5.

In Filter 3, during Stage 1 and major part of Stage 2, the particles were captured within the fabric. No visible deposition was observed on the sand surface and no head loss increase was registered within the sand bed until Day 11 of the filter operation. After another 5 days, the head loss had developed significantly with a visible layer on sand bed.

The sand bed of Filter 4 showed no visible deposition (Plate 4.1 f). All particles were essentially captured on and within the fabric. This was also confirmed by the results for turbidity values of the filtrates after fabric, shown in Section 4.2.6.2, which showed that fabric layer captured most of the turbidity.

From the above observations, it is clear that the total thickness of the fabric had a significant effect on particle capture behaviour. The particle capture appeared to proceed sequentially in the fabric layers for most particles. From Day 0 to Day 5, no deposited layer as well as head loss increment were observed on the sand bed of Filters 2, 3, and 4. During this period, the particles were captured within the top two fabric layers. Following the same trend, five layers of fabric in Filter 3 captured most particles for 11 days, and head loss also increased significantly in the sand bed after 11$^{th}$ day. While, 10 layers of fabric in Filter 4 continued to capture particles for up to 20 days.

As bentonite clay (particles sizes: 90 % passing size - 7 μm, 10 % passing size - 2.7 μm, and maximum size 75 μm) was the main turbidity causing impurity in this run, the developed layer had mostly the bentonite clay particles and was grey in colour. Even though it was considered that during filter Run 1 the biological activity was limited, but not completely stopped, due to the raw water characteristics and low level TOC, the presence of colonies other than total and fecal coliform in feed and filtrates indicated a minimum level of bio population being present in the developed layer or the *schmutzdecke*. Besides, different types of algae and dead algae, coming from the algae culture mixed in the raw water, was present in the *schmutzdecke*.

The study of Mbwette (1989) showed that, 4 layers (14.4 mm) and 6 layers (21.6 mm) of NWF provided good protection against particles of size range of 4 to 64 μm from escaping, which agrees with the present study. Besides, in Run 1 of the present study, the size range of the particles was in the lower range as compared to the study by Mbwette. This established the effectiveness of fabric in capturing the lower sizes of the particles present in the influent water for SSF. Typically, the surface water influents to the SSF carry most of the particles in the size range of 3.5 to 10 μm (Faust and Aly 1999) other than some species of bacteria, viruses and colloidal particles, and similar size range particles were used as turbidity source in Run 1.

### 4.2.5 Filter Run Time and Sand Bed Protection Time

Filter run time is defined as the length of duration starting from the time of filter operation start, initial or after cleaning, to the time when a specified head loss is registered across the filter bed. For normal SSF application, a value between 0.45 to 2 m of head loss is typically used (Visscher et al. 1987). The selection of terminal head loss depends on the maximum head loss allowed by the filter structure. In the present study, the filter setup allowed the maximum head loss of 1050 mm, and this value was used in defining the filter run.

In this filter run, all filters were operated till 20$^{th}$ day, when the maximum head loss was occurred or the required flow rate could not be maintained. Only Filter 2 did not reach to the maximum head loss. According to the definition presented, Filters 1, 3 and 4 had similar filter run time of 17 days. From the head loss development trend of Filter 2, it was estimated that it could be operated for another 2 to 3 days. Mbwette's study showed increase in filter run time, whereas inclusion of a similar type of fabric in Run 1 of the present study did not increase the filter run time.

In SSF, filter cleaning by scraping a layer of sand bed at the top is a laborious and time consuming process. This also results in loss of treated water from consumption due to unacceptable quality for a period following filter cleaning resulting from removal of *schmutzdecke* and disturbance of sand bed. Any practice that would extend the filter run time for the sand bed would reduce the time and labour in filter cleaning, and is therefore expected to make it more attractive, and possibly more economical, for water treatment applications, especially in developing countries where cleaning is expected to be done manually.

The extension in sand bed run time provided by the fabric layers was examined in terms of sand bed protection time, which is defined as the time from the start of filter run till a measurable increase in head loss is registered in the sand bed.

In Filter 1, particles started to deposit on sand from the first day of filter operation because there was no fabric. Filter 2 showed particles deposition (visible layer) on top of sand bed on Day 6 of Filter operation when the head loss in sand bed was 48 mm. Until Day 5 the head losses within sand beds were close to the clean bed head loss of 22 mm, which indicated that 5 days of sand bed protection time was offered by two layers of fabric. Similarly, Filter 3 had 11 days and Filter 4 had more than 20 days of sand bed protection time. It is clear from these observations that the thicker the fabric on the sand surface, the higher was the filter sand bed protection time. Figure 4.8 shows the effect of fabric thickness on sand bed protection time during Run 1. It is clear that the sand bed protection time was increased with the fabric thickness linearly.

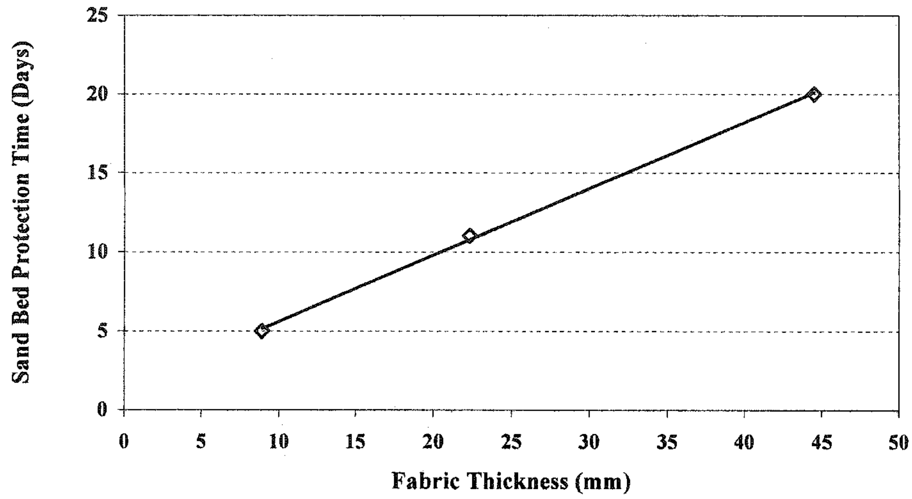



**Figure 4.8:** Fabric Thickness vs Sand Bed Protection Time (Run 1)

### 4.2.6 Filtered Water Quality

#### 4.2.6.1 pH

The pH values of the filtrates were measured on 12 different days in this phase. Table 4.4 shows the pH of the feed and final filtrates in different filters. The observations showed that all the pH values were within the range of 6.78 to 7.92.

**Table 4.4:** pH of Feed and Filtrates (Run 1)

| | Feed | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|---|
| **Average*** | 7.43 | 7.31 | 7.35 | 7.62 | 7.64 |
| **Lowest** | 7.86 | 6.78 | 6.96 | 7.26 | 7.20 |
| **Highest** | 6.83 | 7.85 | 7.91 | 7.87 | 7.92 |

* Based on 21 Samples

#### 4.2.6.2 Turbidity

Turbidity removal efficiencies of all filters were >97 % from the 2$^{nd}$ day of the filter operation. The daily filtrates turbidity and the percentage removal efficiencies for different filters are shown in Appendix H.2 (Table H.4). For calculating the percentage removal efficiency, feed turbidity was measured 16 hours before the filtrate turbidity measurements because the residence time for the filters was about 16 hours. It is observed that the overall average turbidity removal efficiencies were 98.1 %, 98.5 %, 98.6 % and 98.7 % for Filters 1, 2, 3 and 4, respectively and the final filtrate turbidity for all the filters was always less than 0.5 NTU. The overall average final filtrate turbidity values were 0.20, 0.15, 0.15, and 0.15 NTU for Filters 1, 2, 3 and 4, respectively. Mbwette (1989) reported that filter without fabric and with 2, 4,and 6 layers of fabric (14,400 $m^2/m^3$ specific surface area, and 7.2 mm of one layer thickness) produced filtrate with mean turbidity of 0.23, 0.23, 0.21, and 0.21 NTU, respectively for the influent water turbidity of 1.1 to 4.4 NTU. The result indicated that change in the final filtrate turbidity by addition of fabric was insignificant. Similar results are found in Run 1 of this study.

Table 4.5 shows the average turbidity of final filtrates during different time periods of filter operation. It is clear from the observations that filtrates turbidity values gradually became lower, which is expected for any SSF. Figures 4.9 to 4.14 show the feed, filtrates after fabric and final filtrates turbidity of different filters.

**Table 4.5** Average Turbidity values of Filtrates at Different Stages (Run 1)
(Turbidity Unit- NTU)

| **Period** | **Feed** | **Filter 1** | **Filter 2** | **Filter 3** | **Filter 4** |
|---|---|---|---|---|---|
| Day 0-Day 5 | 10 | 0.25 | 0.20 | 0.20 | 0.20 |
| Day 5-Day 11 | 11 | 0.20 | 0.15 | 0.15 | 0.10 |
| Day 11-Day 20 | 11 | 0.15 | 0.15 | 0.10 | 0.10 |

In case of the filtrates after the fabric layers, the overall average removal efficiencies were 74.4 %, 96.1 % and 98.0 % for Filters 2, 3 and 4, respectively. This indicates that thicker fabric in Filter 3 (22.3 mm fabric) and Filter 4 (44.5 mm fabric) removed the major portion of the turbidity causing particles, while Filter 2 (8.3 mm thick) fabric allowed some particles to escape. The increase in particle capture with thicker fabric layer can be explained by the depth and adsorptive filtration mechanisms. In thicker fabric layer, the tortuous paths for water flow are increased due to winding nature of fibre and the probability of particles and fibres collisions and attachments by adsorption is increased. This contributes to the higher particles removal.

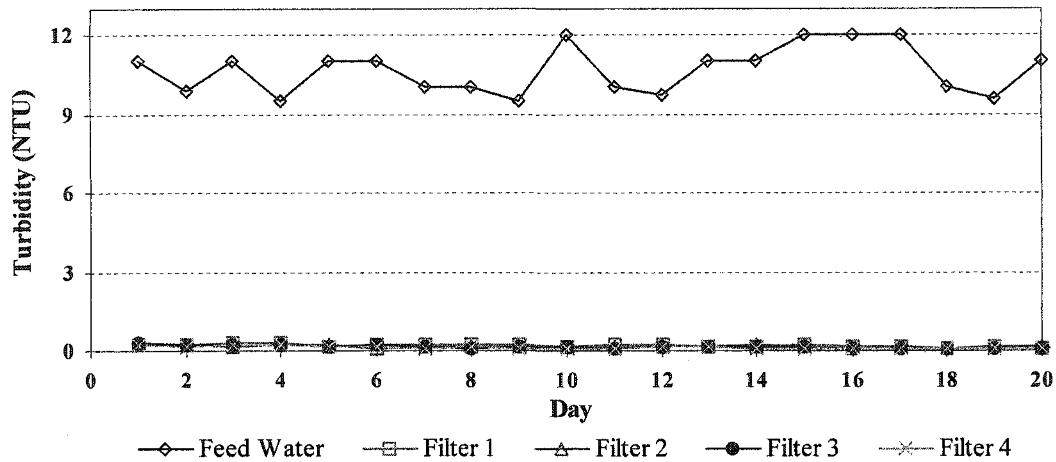



**Figure 4.9:** Feed and Final Filtrate Turbidity (Run 1)

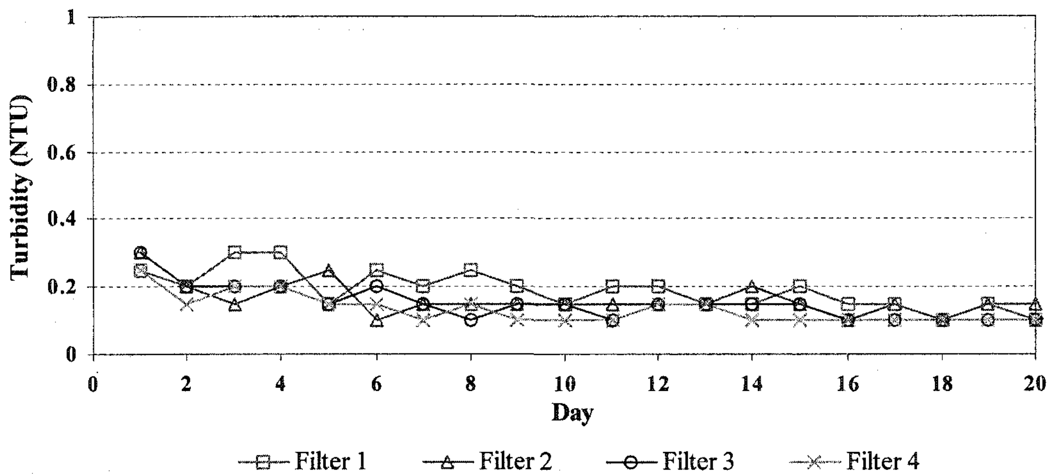



**Figure 4.10:** Final Filtrate Turbidity (Run 1)

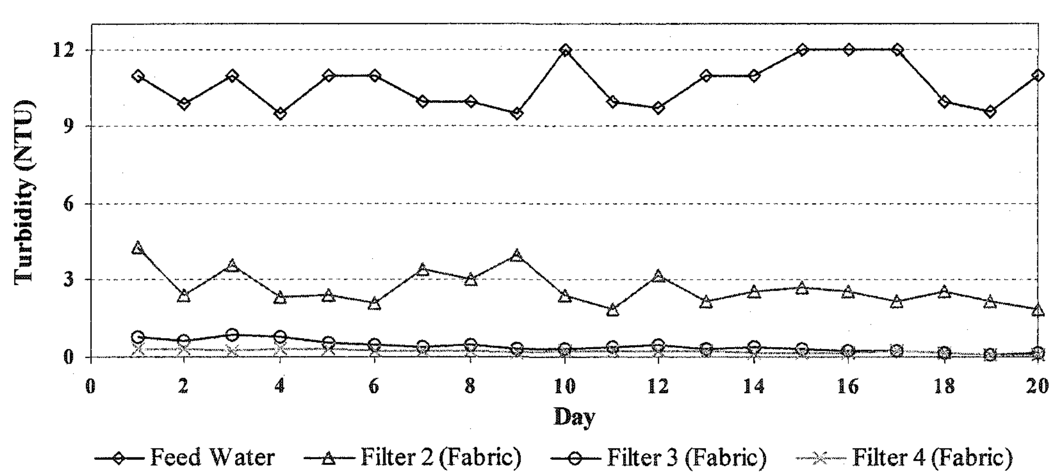



**Figure 4.11:** Feed and Filtrate after Fabric Turbidity (Run 1)

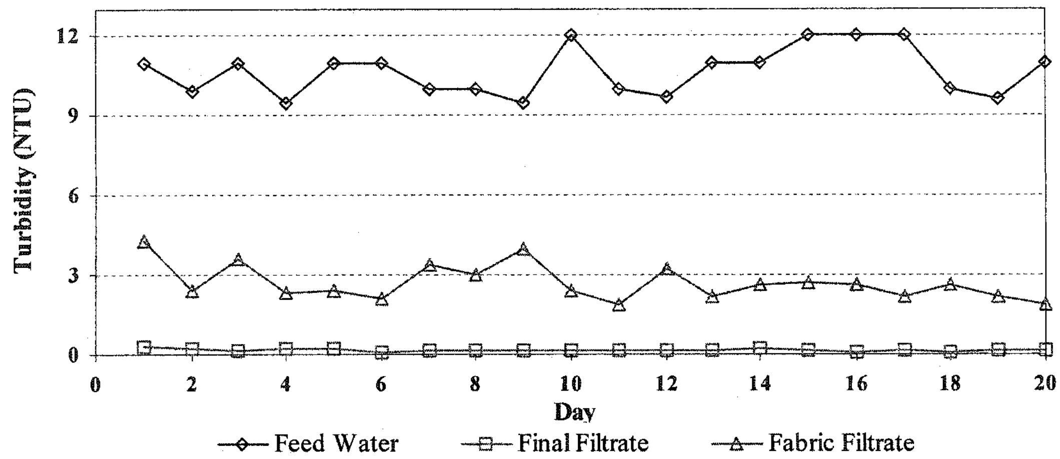



**Figure 4.12:** Turbidity of Filtrates in Filter 2 (Run 1)

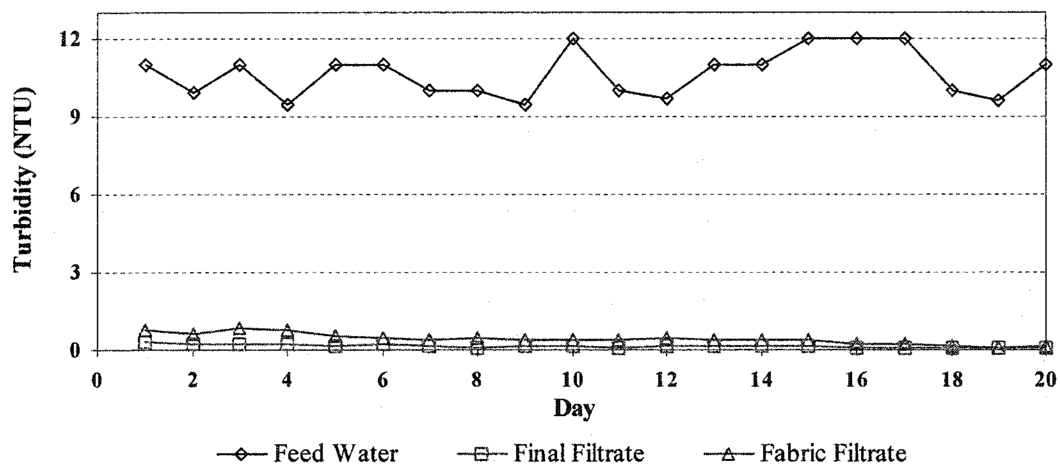



**Figure 4.13:** Turbidity of Filtrates in Filter 3 (Run 1)

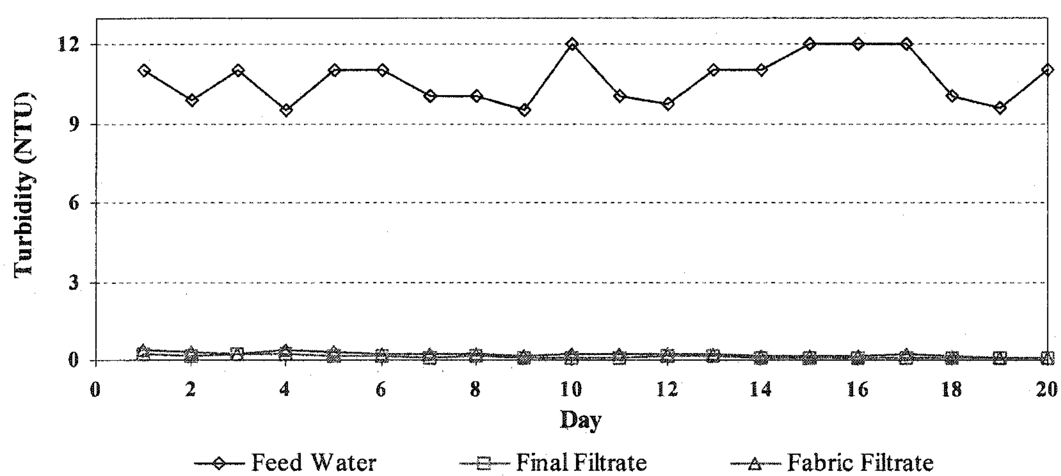



**Figure 4.14:** Turbidity of Filtrates in Filter 4 (Run 1)

Although final filtrate turbidity values of filtrates from the filters with fabric are comparable with the filter without fabric (control filter), the turbidity of filtrates after fabric indicated that top few layers of the fabric were capable of removing bulk portion of the turbidity causing particles from the feed water. This observation is supported by the head loss values and particles deposition patterns. Thus, appropriate thickness of fabric can protect the sand bed from particle deposition.

#### 4.2.6.3 TOC

The daily filtrate TOC and percentage removal efficiencies for different filters are shown in Appendix H.3 (Table H.7). For the calculation of percent removal efficiency, the feed TOC was measured 16 hours before the filtrate TOC. The TOC in filtrates were measured on 10 different days and, in all the cases, the TOC values were less than 0.5 mg/L. From Table H.7, it is observed that overall average TOC removal efficiencies were 40.9 %, 41.5 %, 44.4 % and 46.7 % for Filters 1, 2, 3 and 4, respectively.

Figure 4.15 shows the feed water TOC during this filter run. Figure 4.16 shows the percentage removal of TOC in different filters, both in fabric and sand bed, whereas Figure 4.17 shows the percentage removal of TOC across the fabric in different filters. From these figures, it is clear that TOC removal efficiencies of control filter and filters with fabric are comparable, and the removal efficiencies increased with the time of filter operation. The increased TOC removal efficiencies could be related to the increased turbidity removal efficiencies since turbidity contributed to the particulate organic carbon, and also an increase in bioactivity in the filters.

From Figures 4.15 to 4.17, it is observed that, from Day 0 to Day 9 sand beds in all the filters dominated the TOC removal. However, after 9$^{th}$ day, fabric dominated the removal, which indicates that *schmutzdecke* was developed during that time and some bioactivity was present there.

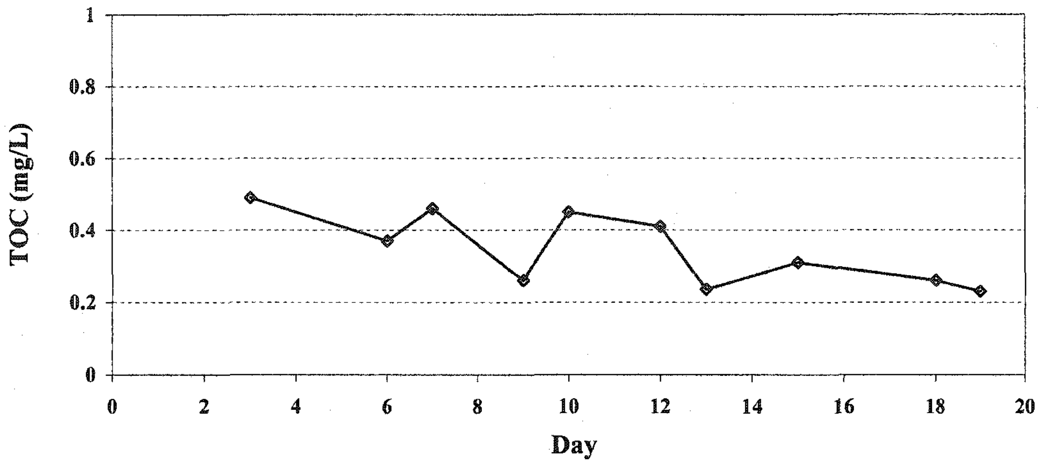



**Figure 4.15:** Feed Water TOC (Run 1)

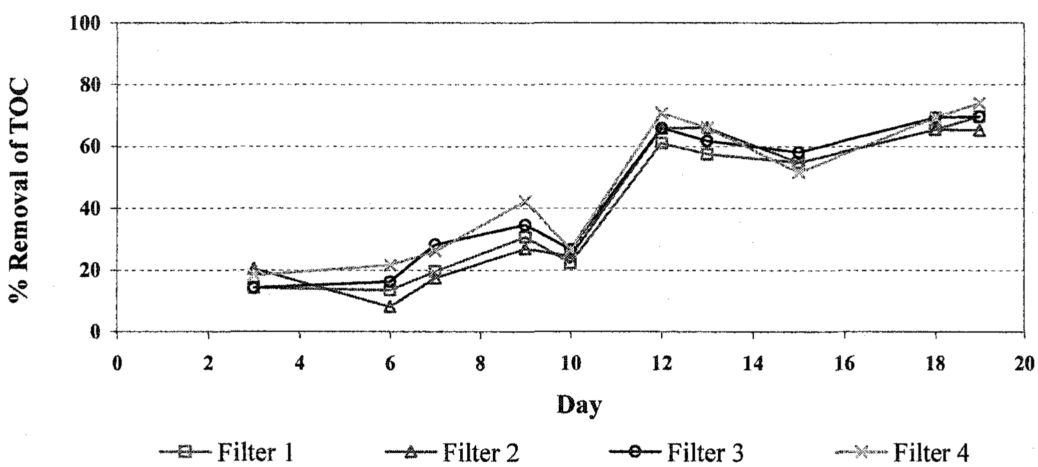



**Figure 4.16:** Percent Removal of TOC in Filters (Run 1)

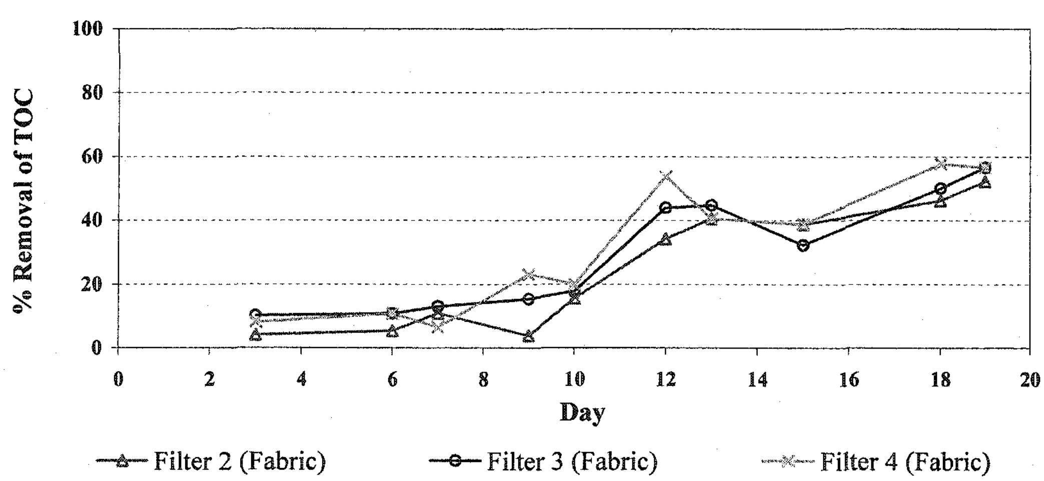



**Figure 4.17:** Percent Removal of TOC in Fabric (Run 1)

Typically, surface water TOC varies within the range of 2.5 to 9 mg/L (Graham 1999), while the average TOC of the influent for the present run was 0.37 mg/L. Generally, TOC removal efficiency of SSF is less than 25 % for natural surface water and depends on the biofilm in the filter (Collins et al. 1991; Cleasby 1991). Higher removal values were found in the present run when compared to the TOC removal of natural surface water. This might be due to the difference in composition of the raw water and lower bioactivity within all the filters in Run 1.

### 4.2.7 Filter Cleaning and Head Loss after Cleaning

At the end of filter Run 1, the supernatant water from all the filters was drained and the top portions of the filters were dismantled. The fabrics were removed from the filters with fabric, and 25 mm of top sand was scraped and removed from all the filters. All the fabric layers were washed by soaking them in water, and by applying tap water flow with moderate pressure from the reverse side of the fabric. These washed fabric layers were placed in the filters again, and after assembling the filters, clean tap water was passed through the filters and head losses were recorded as shown in Table 4.6.

**Table 4.6:** Head losses after Filter Cleaning (Run 1)
(Head Loss Unit – mm)

| | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|
| **Fabric** | - | ND* | ND | ND |
| **Sand Bed** | 24 | 22 | 23 | 23 |
| **Total** | 24 | 22 | 23 | 23 |

* ND- Not detected

From these results, it is clear that most of the particles were captured on the top 25 mm of sand beds and/or top few layers of the fabric. It is also clear that cleaning of the fabric layer by pressurized tap water had remove most of the trapped particles.

## 4.3 Phase II

The main objective of this phase was to examine the development of biological layer in the filters with and without fabric, and its effect on the treated water quality with influent turbidity < 2 NTU. The effect of elevated TOC levels, approximately 7 mg/L, on the development of the biological layer and filter performance was also examined. Elevated TOC was maintained from the 22$^{nd}$ day of the filter operation, while maintaining the influent turbidity of less than 2 NTU. In this phase, all filters were operated for 61 days, although after 58$^{th}$ day, the required flow rate of 0.1 m/h could not be maintained in all the filters.

### 4.3.1 Influent Water Characteristics

A summary of the simulated raw water characteristics is shown in Table 4.7. The daily raw water characteristics for this filter run are shown in Appendix E (Table E.6).

**Table 4.7:** Raw Water Characteristics (Run 2)

| **Parameters** | | **Average ± SD** | **Maximum** | **Minimum** | **No: of Samples** |
|---|---|---|---|---|---|
| Temperature, (°C) | | 21.9 ± 1.1 | 23.4 | 19.1 | 62 |
| DO, (mg/L) | | 8.51 ± 0.92 | 10.2 | 6.95 | 62 |
| PH | | 7.17 ± 0.34 | 7.78 | 6.43 | 62 |
| Turbidity, (NTU) | | 1.7 ± 0.19 | 2 | 1.4 | 62 |
| TOC, (mg/L) | Day 0-21 | 0.41 ± 0.12 | 0.63 | 0.22 | 22 |
| | Day 22-61 | 6.78 ± 1.5 | 9.03 | 4.35 | 40 |
| Nitrate-Nitrogen, (mg/L) | | 1.53 ± 0.32 | 2.1 | 0.95 | 35 |
| Ammonia-Nitrogen, (mg/L) | | 0.58 ± 0.19 | 0.91 | 0.22 | 35 |
| Total Coliform (CFU/100 mL) | Day 0-35 | <1 | <1 | <1 | 7 |
| | Day 36-61 | 5910 ± 2288 | 10930 | 3520 | 13 |
| *E. coli* (CFU/100 mL) | Day 0-35 | <1 | <1 | <1 | 7 |
| | Day 36-61 | 410 ± 184 | 780 | 160 | 13 |
| Chlorophyll- A, (μg/L) | | 3.95 ± 1.27 | 1.2 | 5.8 | 25 |

* From 36$^{th}$ day, tap water was filtered through AC filter for preparing feed water.
* SD – Standard deviation; No: – Number.

It can be seen that the raw water turbidity was within the range of 1.4 to 2 NTU (average = 1.7 NTU), which was lower than the maximum recommended value of turbidity (5 NTU) of raw water for SSF (Cleasby 1991). No bentonite clay was added to prepare the raw water, thus all the turbidity was contributed by the treated wastewater effluent and algal culture added to the simulated raw water. The TOC of the raw water was low (0.22 to 0.63 mg/L, average = 0.41 mg/L) for first 21 days of the filter operation, which might have been a limiting factor for biogrowth on the filter. Bellamy et al. (1985) have stated that bioactivity and biogrowth could be limited due to low TOC in raw water. From the 22$^{nd}$ day, glucose was mixed in the raw water to increase TOC level (average = 6.78 mg/L). Since the natural surface water TOC varies from 2.5 to 9 mg/L (Graham 1999), the TOC applied from Day 22 to Day 61 in this run is considered as high.

For the first 35 days of the filter operation, dechlorinated tap water was used for the preparation of raw water. It was mentioned earlier that due to tap water toxicity coliform were not surviving in the raw water beyond 8 hours. Thus, various efforts were made to overcome this limitation during this period and water filtered through AC filter was found to be suitable for the survival of coliform in the raw water. From 36$^{th}$ day, the tap water was filtered through AC filter before using it for the preparation of simulated raw water.

### 4.3.2 Clean Bed Head Loss

At the end of Run 1, 25 mm of sand layer was removed from all the filters, and before starting Run 2, additional 30 mm of sand layer was scraped and cleaned from all the filters. Thus the sand bed depth in Run 2 was reduced by 55 mm as compared to Run 1. New NWF layers were used in the Filters 2, 3 and 4. After installation of all the filters, clean tap water was passed through the filters for 10 days to minimize residual bioactivity in the remaining sand bed from Run 1. The initial clean bed head losses were measured using clean tap water when the turbidity was less than 0.1 NTU. Table 4.8 shows the clean bed head losses for all the filters at filtration rate of 0.1 m/h before starting Run 2.

**Table 4.8:** Clean Bed Head Losses before Run 2 at Filtration Rate of 0.1 m/h
(Head Losses Unit – mm)

| | **Filter 1** (0.9 m Sand Bed + 0 mm thick fabric) | **Filter 2** (0.9 m Sand Bed + 8.9 mm thick fabric) | **Filter 3** (0.9 m Sand Bed + 22.3 mm thick fabric) | **Filter 4** (0.9 m Sand Bed + 44.5 mm thick fabric) |
|---|---|---|---|---|
| **Fabric** | - | ND* | ND | ND |
| **Sand Bed** | 18 | 21 | 18 | 20 |
| **Total** | 18 | 21 | 18 | 20 |

* ND – Not detected.

The initial clean bed head losses in different filters in this case were 2 to 4 mm less than those found before filter Run 1. This may be due to the reduction of sand bed depth by about 55 mm. The other reason could have been the higher temperature (23°C) of the water during the clean bed head loss test.

### 4.3.3 Head Loss Development

Figures 4.18 to 4.23 illustrate the head loss development in all the filters during filter Run 2. All plots are based on the average daily head loss values. Figure 4.18 shows the total head losses in different filters. It is clear that the overall filter operation time of 61 days can be divided into 4 stages (Stage 1: Day 0 to 36; Stage 2: Day 36 to 44; Stage 3: Day 44 to 58; and Stage 4: Day 58 to 61) based on the head loss development patterns. During Stage 1, Filter 1 showed head loss increment rate of 3 mm/d from Day 0 to Day 22, and 13 mm/d from Day 23 to Day 36. This increment in rate could be due to the increase in TOC level in the raw water from Day 22, which increased the bioactivity in the filter. Filters 2, 3, and 4 showed comparatively low head loss increments in Stage 1. The increment rates were 1.3 mm/d, 0.75 mm/d, and 0.89 mm/d, respectively.

In Stage 2, head losses increased by 211 mm, 155 mm, 166 mm, and 143 mm in Filters 1, 2, 3, and 4, respectively. Between Day 38 and Day 44, the head losses again decreased to lower head loss values in all filters. On the 44$^{th}$ day, the head losses decreased to 76 mm, 38 mm, 27 mm, and 22 mm in the Filters 1, 2, 3, and 4, respectively. During this Stage,

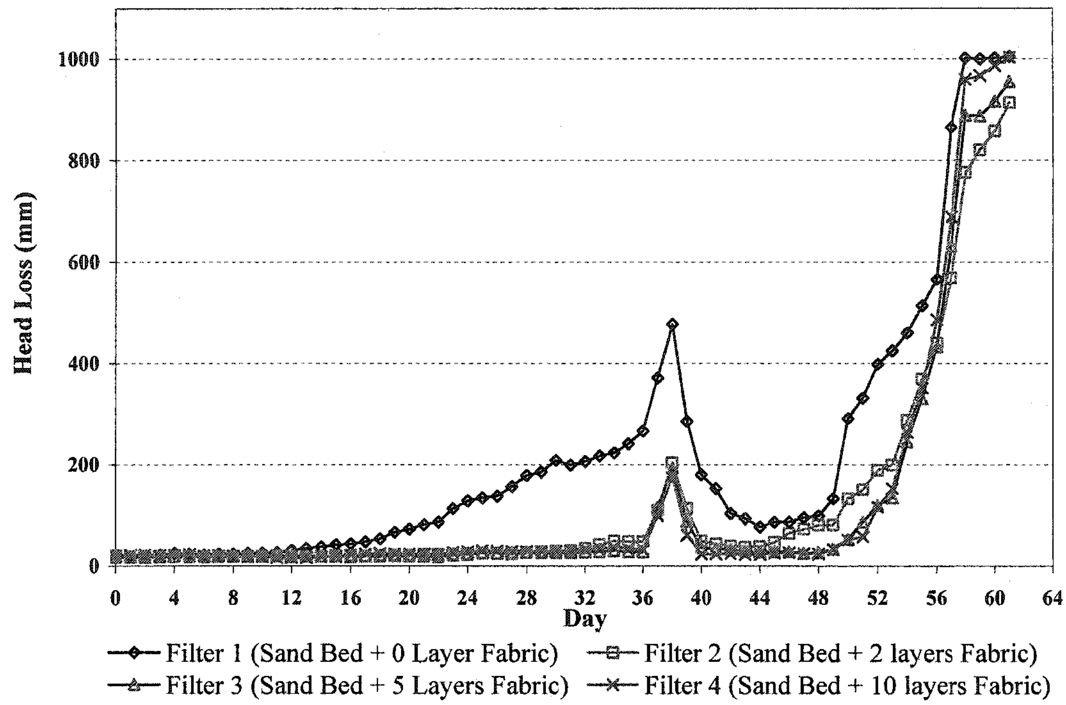



**Figure 4.18:** Comparison of Total Head Losses (Run 2)

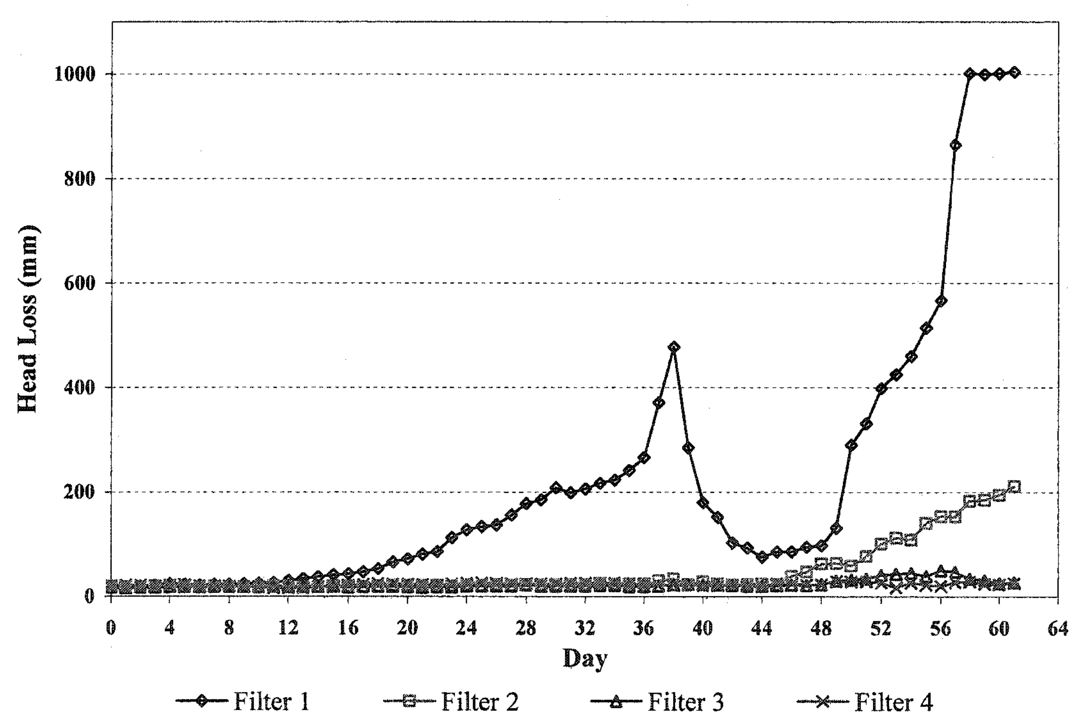



**Figure 4.19:** Comparison of Head Losses Across Sand Beds (Run 2)

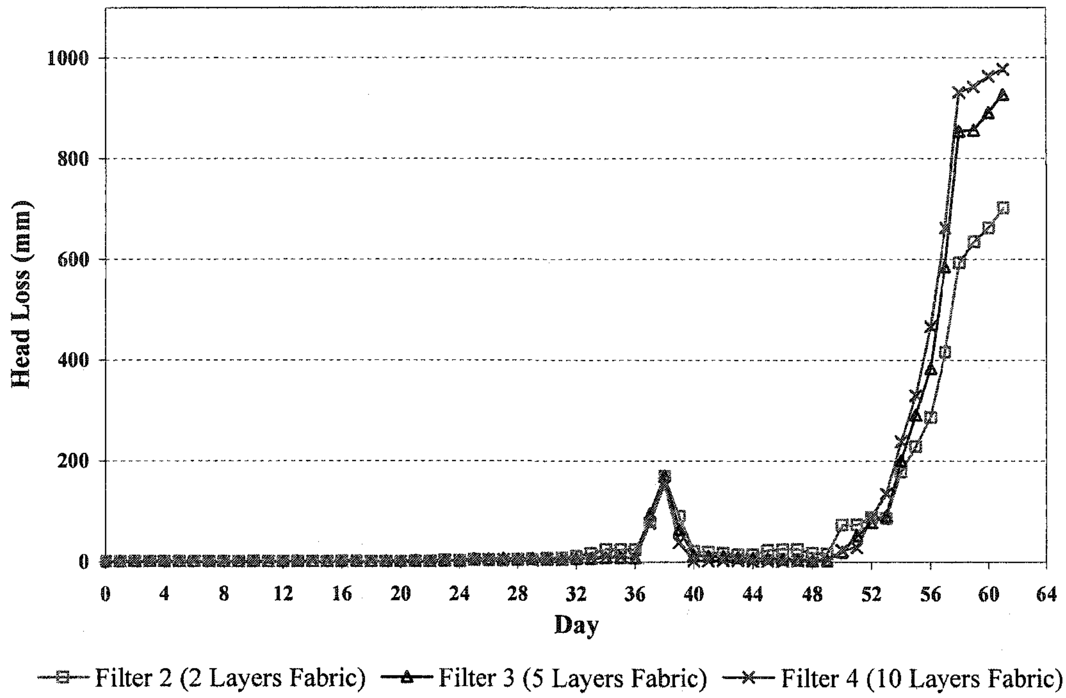



**Figure 4.20:** Comparison of Head Losses Across Fabric (Run 2)

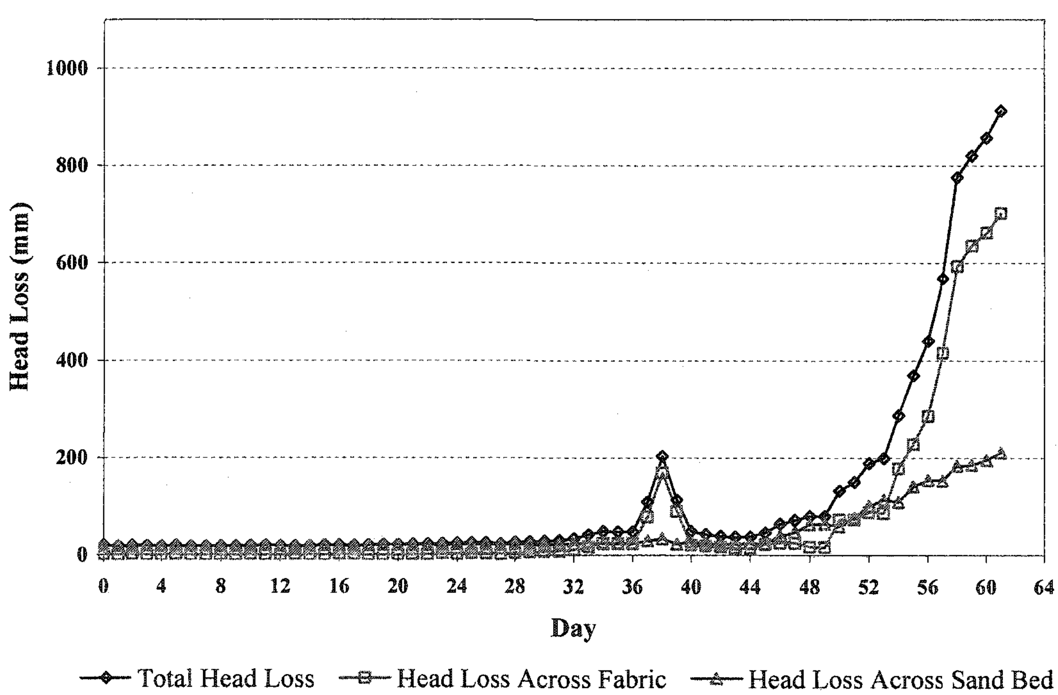



**Figure 4.21:** Head Losses in Filter 2 (Run 2)

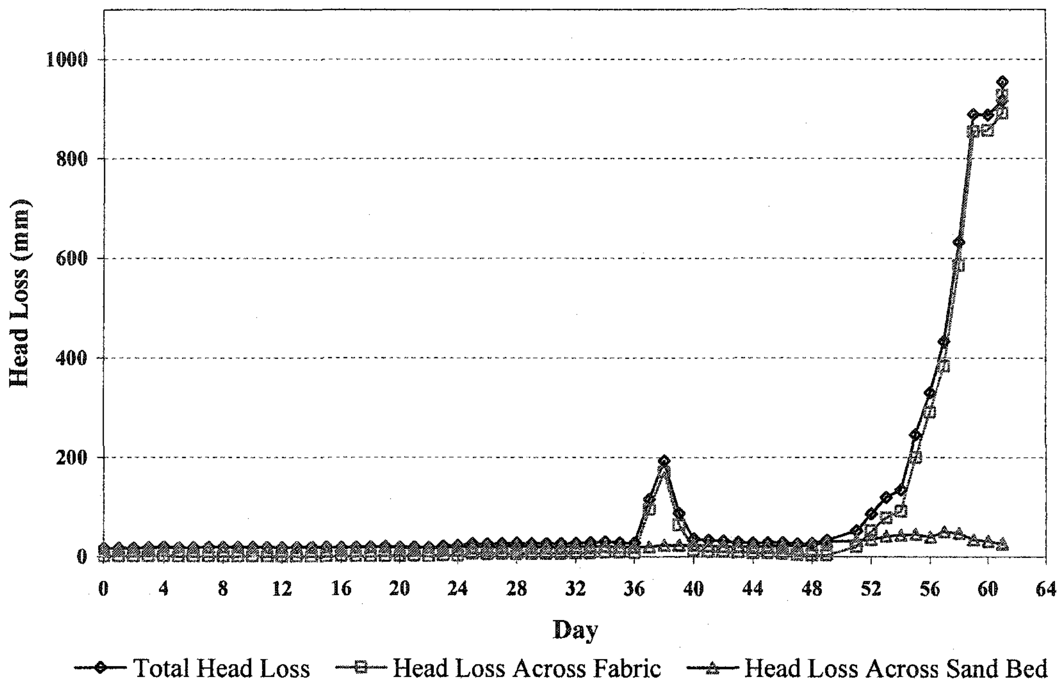



**Figure 4.22:** Head Losses in Filter 3 (Run 2)

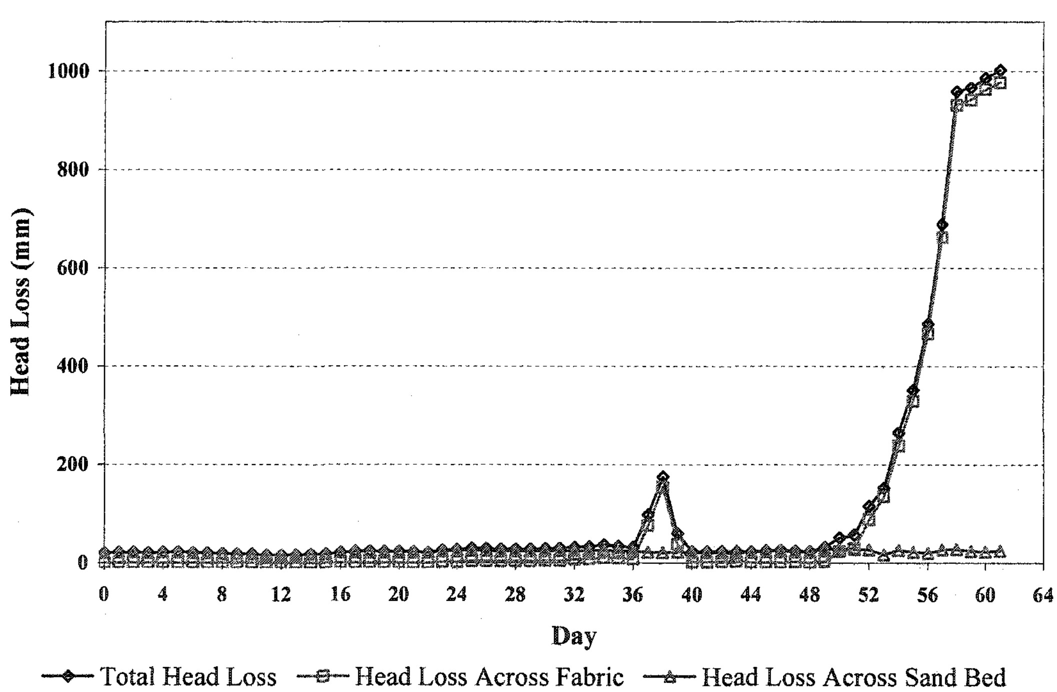



**Figure 4.23:** Head Losses in Filter 4 (Run 2)

Filters 2, 3, and 4 had similar head loss development patterns and the values were also close. Filter 1 had higher head losses as compared to others. The increase of head losses in all the filters from 36th day might be due to the growth of biomass on the top surface of filter media. The raw water from that day was prepared by using AC filtered tap water, which allowed the survival of coliform and other microorganisms. The toxicity free water, high TOC, and high temperature accelerated the biogrowth in the filters. However, decrease in the head losses in all the filters was not expected. Similar head loss development behaviour was reported by Toms and Bayley (1988). Change in nutrients, and ecology in the *schmutzdecke* might have been the reason for this type of head loss behaviour.

During Stage 3, Day 44 to Day 58, the total head losses in all the filters increased exponentially. The head loss increment rates were 66.1 mm/d, 52.7 mm/d, 61.5 mm/d, and 66.9 mm/d for the Filters 1, 2, 3, and 4, respectively. In this stage initially Filter 2 had higher head losses when compared to Filters 3 and 4, while after Day 55 those were less. Figure 4.24 shows the trend lines of the total head loss developments for the different filters for this stage of the filter operation.

In Stage 4, for the Filters 1, 3 and 4 the head loss increment rates were 1 mm/d, 22 mm/d, and 14 mm/d, respectively, and for the Filter 2 it was 60 mm/d, which was close to the increment rate at Stage 3 (52.7 mm/d). From the of the trend lines of total head loss developments in Stage 3 (Figure 4.24), it is found that on 59th day the head loss values were rose to 1281 mm, 1380 mm, and 1326 mm in Filters 1, 3 and 4, respectively. These were more than the maximum available head loss of 1050 mm allowed by the setup. For the Filter 2, it happened on 60th day. As a result, during Stage 4, the filtration rate became less than the design filtration rate of 0.1 m/h, and consequently the head loss increment rates became lower than in Stage 3.

Similar to filter Run 1, the total head losses in this run in different filters reached to the maximum allowed head loss of 1050 mm almost simultaneously, whereas, Mbwette's study showed that occurrence period of 350 mm head loss (maximum allowed in that study) was increased by a factor of 1.5 to 2 for filters with 2, 4, and 6 layers of fabric as

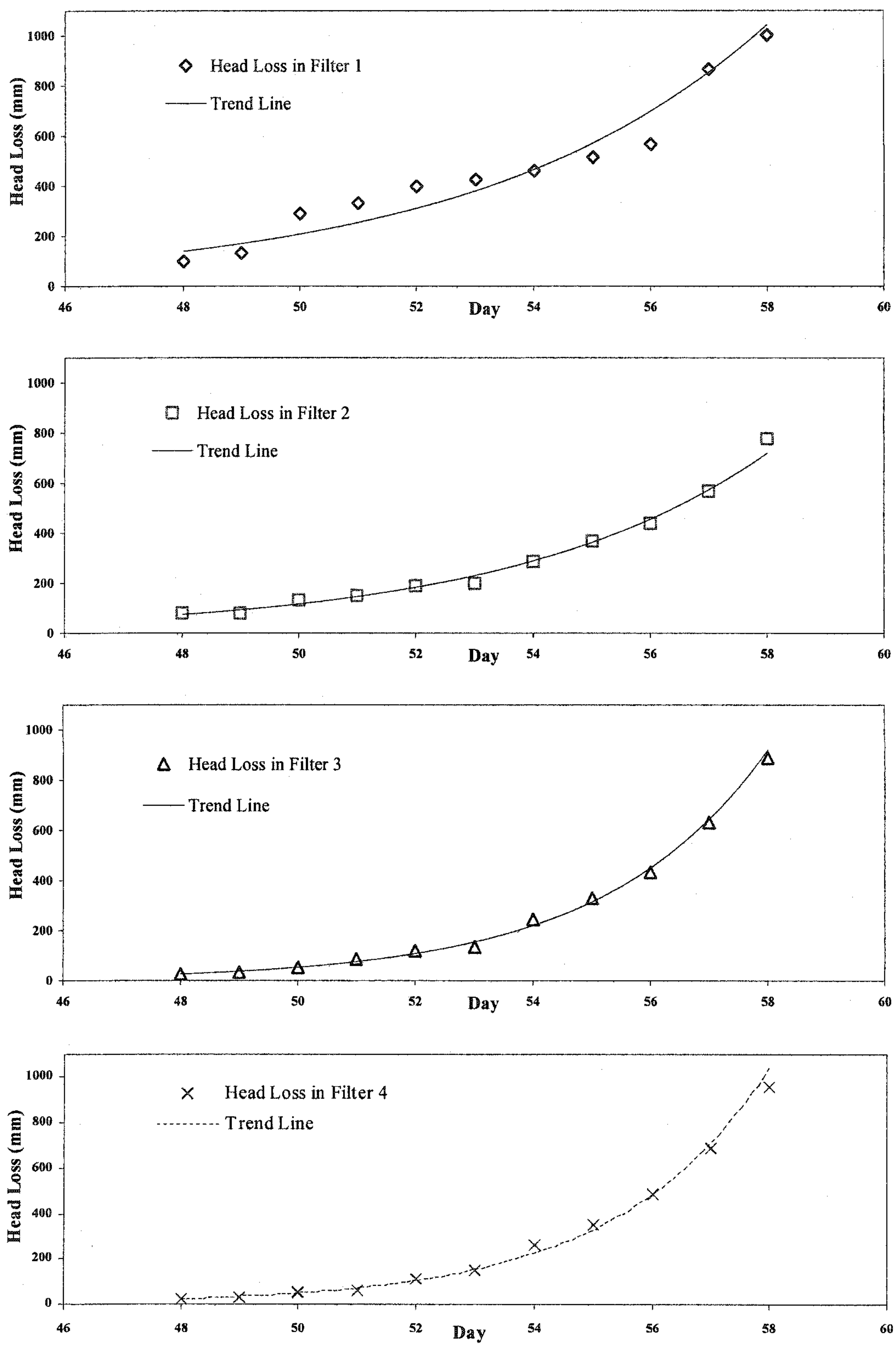



**Figure 4.24:** Trend Lines of Head Loss Development in Filters during Run 2
(Day 48 to Day 58)

compared to filter without fabric. However, if 350 mm head loss was considered as the end point of filter operation for this run, head loss in Filter 1 reached that value on the 37th day, and head losses in Filters 2, 3, and 4 reached that value simultaneously on the 55th day. This is about 1.5 times the control filter run time. However, the change in fabric depth in Run 2 showed no difference in filter run time.

Figure 4.19 shows the head losses in sand beds. In Filter 1, there was no fabric, and total head loss was all contributed by sand bed. Head losses in the sand bed started rising at a higher rate from Day 46 in Filter 2. Filter 3 showed slight increment in head loss from the 49th day, and the maximum head loss was 50 mm on 61st day. Sand bed in Filter 4 also showed no noticeable head loss increment during the entire filter run.

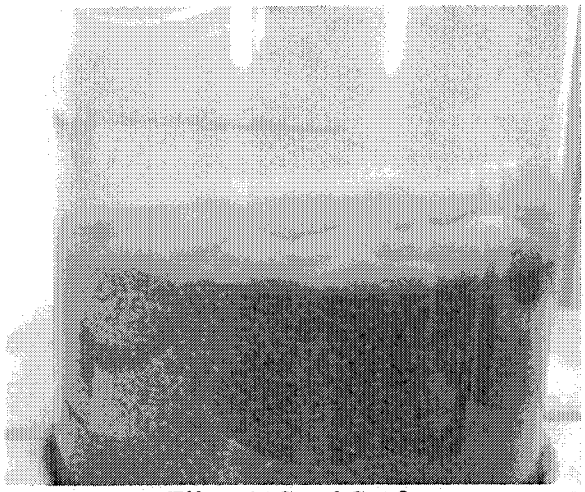
Figure 4.20 shows the comparative head losses in the varying thickness of fabrics in different filters. The head loss development patterns and values were similar for all the filters with fabric. Even though the fabric in Filter 2 was showing slightly higher head losses than those of the Filters 3 and 4, after Day 53 those became lesser. On the last day of the filter operation the head losses across fabrics were 702 mm, 927 mm, and 977 mm in Filters 2, 3, and 4, respectively.

Figures 4.21, 4.22 and 4.23 show the total head losses, contribution of sand beds and fabric layers to the total head losses of Filters 2, 3, and 4, respectively. For Filters 3 and 4, the total head losses were mostly contributed by the fabric. For Filter 2, sand bed had some contribution to the total head loss from Day 46 with the maximum of 211 mm on 61st day.

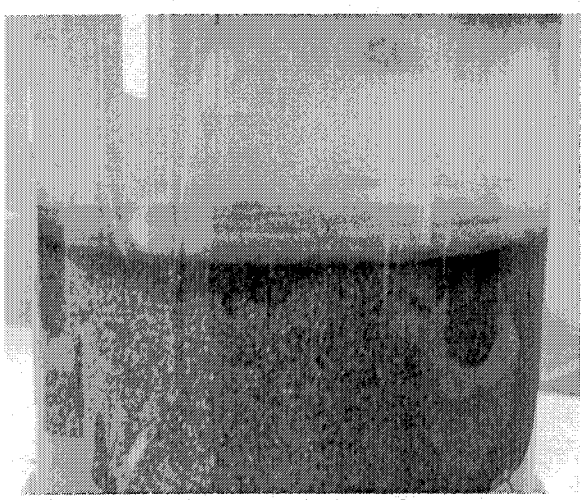
### 4.3.4 Particle Deposition and Development of *Schmutzdecke*

Plate 4.2 shows the developed layer on the fabric and sand surface of different filters at the end of filter run.

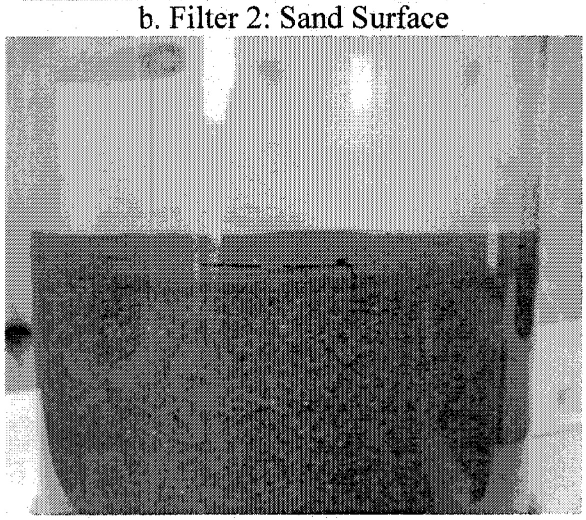
During Stage 1, only Filter 1 showed a thin layer of deposited materials on the sand surface and significant amount of head loss development. No layer was seen on the fabric



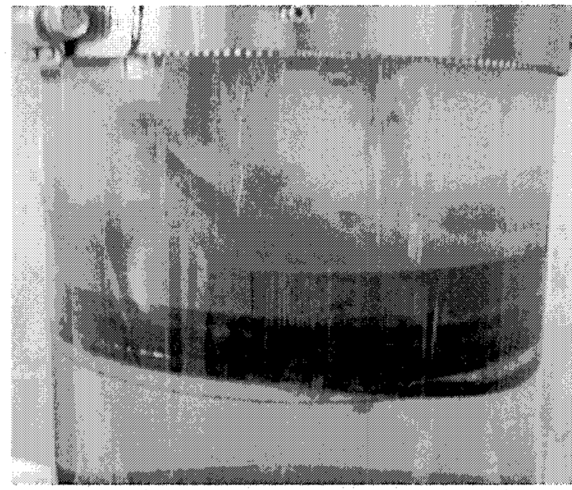
a. Filter 1: Sand Surface



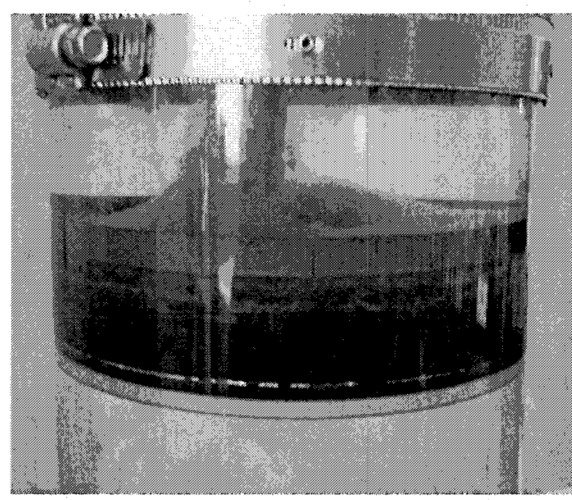
b. Filter 2: Sand Surface



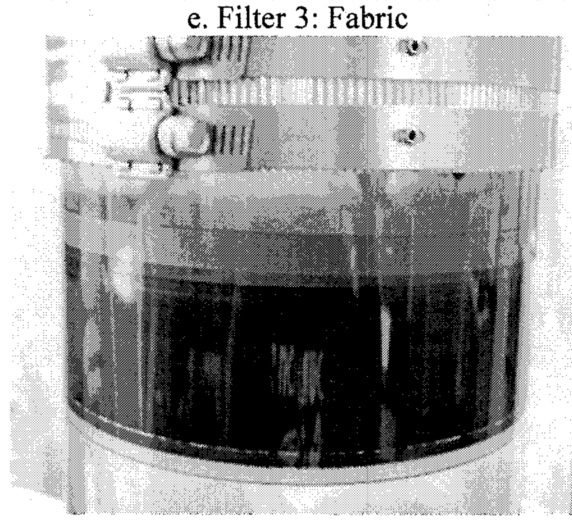
c. Filter 3: Sand Surface



d. Filter 2: Fabric



e. Filter 3: Fabric



f. Filter 4: Fabric

**Plate 4.2:** *Schmutzdecke* in Different Filters (Run 2)

surface or on the sand surface for the other filters. This observation indicated that fabric captured the particles and stored within it. For Filter 1, sand is the first filter media for raw water to pass through. The sand bed provided smaller pore openings, less porosity and almost a plane surface to form a thin compact layer which contributed to the higher head loss. On the other hand, Filters 2, 3 and 4 had fabric as the first media for raw water to pass through. Since the fabric has higher porosity, larger opening sizes, rough top surface and higher particles storage capacity, particles were captured within the fabric and no visible layer was found on the fabric surface. Moreover, particles, captured in the fabric, did not affect the hydraulic conductivity of the fabric. This was also indicated by the head loss values.

At the beginning of Stage 2, because of high TOC, high temperature of 21.9 °C on 36$^{th}$ day, and absent of raw water toxicity, significant biogrowth (white layer) was observed on the top media surfaces of all the filters. This biogrowth increase the head losses in all the filters. After 2 days, the amount of biomass in the *schmutzdecke* seemed to be decreased, and the head losses had started to decrease. It was difficult to provide the explanation for the head loss decrement. While, the observation indicated that the plausible reason could be the destruction of developed biomass due to predation by some dominant species during that time. During this Stage, filters with fabric showed no biogrowth on the sand surface.

In Stage 3, the *schmutzdecke* layer again had started to increase in thickness with biomass in all the filters. The head losses had increased exponentially. The TOC consumption rate (results are presented in later section) during this stage explained the higher rate of bioactivity and corresponding biogrowth. From the beginning of this stage, a thin layer was found on the sand surface of Filter 2 along with increment in head loss. While, Filters 3 and 4 showed no visible layer on the sand surface. This indicated that particles were escaping 2 layers of fabric after a certain time of filter operation, while they were captured within 5 and 10 layers of fabric during that period. Similar observation of sequential particle escaping was found during filter Run 1. In Run 2, the raw water turbidity of 1.4 to 2 NTU, as compared to Run 1 (9.2 to 12 NTU), increased the time for occurrence of particle escaping from 2 layers of fabric. During this stage, decrease in biomass and decrease in head loss were not observed as observed in Stage 2.

In all the filters with fabric, removing 1 layer of fabric showed low head loss of 1 mm within the remaining fabric layers. This confirmed that in this run most of the particles were captured on the surface or within the first layer of the fabric. Even though most of the particles were captured on and within top layers, the total thickness of the fabric had significant effect on the particle capture. This was observed from the sequential particle capture behaviour within the fabric. Similar behaviour was found in Run 1.

There was a significant difference between the types of *schmutzdecke* formed in Run 1 and Run 2. In Run 1, the *schmutzdecke* was mostly composed of captured bentonite clay; while, in Run 2, *schmutzdecke* was mainly composed of incoming and/or synthesized biomass. This growth of biomass could be explained from the low raw water turbidity and higher TOC consumption values during that period. The *schmutzdecke* in Run 2 was white in colour and did not form a compact layer. However, the size range of the captured particles could not be determined in this case.

### 4.3.5 Filter Run Time and Sand Bed Protection Time

Although, all the filters were operated for 61 days, after 58$^{th}$ day the required filtration rate could not be maintained in Filters 1, 3 and 4, and in Filter 2 it happened after the 60$^{th}$ day. Considering the filtration rate and occurrence of maximum head loss allowed by the setup, explained in Section 4.3.3, the filter run times were 58 days for Filters 1, 3, and 4, and 60 days for Filter 2.

If 350 mm head loss was considered the end point of the filter run, from the head loss development curve (Figure 4.18), filter run times were found 37 days for Filter 1, and 55 days for Filters 2, 3, and 4. This observation indicated that inclusion of fabric in Run 2 increased the filter run time by a factor 1.5. However, the change in fabric depth (5 layers and 10 layers of fabric) in Run 2 showed no difference in filter run time.

In the previous section, it has already been mentioned that Filter 2 showed particles deposition (visible layer) on top of sand bed along with increment in head loss on Day 37 of filter operation. This indicated that 36 days of filter sand bed protection time was provided by 2 layers of fabric. On the other hand, Filter 3 and Filter 4 showed no visible deposition on the sand bed during entire filter operation. Therefore, 5 layers and 10 layers of fabric provided more than 61 days of sand bed protection time. It is clear from these observations that the thicker the fabric on the sand surface the higher the filter sand bed protection time was achieved. In case of filter Run 1, the relationship between fabric depth and sand bed protection time was linear, while similar relationship could not be found as the filter total head loss reached the maximum values before any deposition was found on the sand bed in Filters 3 and 4.

### 4.3.6 Filtered Water Quality

#### 4.3.6.1 pH

The pH values of the filtrates were measured on 40 different days in this phase. Table 4.9 shows the pH of the feed and final filtrates of different filters. The observations showed that all the pH values were within the range of 6.71 to 7.96.

**Table 4.9:** pH of Feed and Filtrates (Run 2)

| | Feed | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|---|
| **Average*** | 7.17 | 7.44 | 7.62 | 7.65 | 7.65 |
| **Lowest** | 6.43 | 6.71 | 7.38 | 7.37 | 7.25 |
| **Highest** | 7.78 | 7.93 | 7.96 | 7.92 | 7.95 |

* Based on 8 Samples

#### 4.3.6.2 Turbidity

The raw water turbidity for this run was low of 1.4 to 2 NTU, and the turbidity of final filtrates of all the filters were always less than 1 NTU. The daily filtrates turbidity values and the percent removal efficiencies for different filters are shown in Appendix H.2

(Table H.5). From Table H.5, it is found that overall average turbidity removal efficiencies were 60.2 %, 62.5 %, 65.7 % and 70.8 % for Filters 1, 2, 3 and 4, respectively. The overall average final filtrate turbidity values were 0.65, 0.65, 0.55, and 0.50 NTU for Filters 1, 2, 3 and 4, respectively. In case of Run 1, the final filtrate turbidity was always less than 0.5 NTU, even though raw water turbidity was high (9.2 to 12 NTU). The results in this run are in contrast with the results in filter Run 1. This might be due to the different types of particles present in the raw water and the type of *schmutzdecke* formed. For Run 1, bentonite clay was used to increase the turbidity, whereas in Run 2, no clay was mixed. The raw water turbidity in Run 2 was due to the treated wastewater effluent, algal culture, and biogrowth in the raw water tank, supernatant water reservoir and *schmutzdecke*.

Figures 4.25 to 4.30 show the feed, filtrates after fabric and final filtrates turbidity of different filters. Table 4.10 shows the average final filtrates turbidity during different stages of the filters operation.

**Table 4.10:** Average Turbidity of Final Filtrates at Different Stages (Run 2)

| Stages | Filter 1 (NTU) | Filter 2 (NTU) | Filter 3 (NTU) | Filter 4 (NTU) |
|---|---|---|---|---|
| Stage 1 (Day 0-Day 36) | 0.55 | 0.55 | 0.45 | 0.40 |
| Stage 2 (Day 36-Day 44) | 0.75 | 0.70 | 0.65 | 0.55 |
| Stage 3 (Day 44-Day 58) | 0.85 | 0.75 | 0.75 | 0.70 |
| Stage 4 (Day 58-Day 61) | 0.60 | 0.55 | 0.65 | 0.45 |

From the Figure 4.25 and Table 4.10, it is observed that turbidity of filtrates increased in Stages 2 and 3, when the biogrowth was noticed in the filters. Therefore, the increase in filtrate turbidity was due to the escaping of some particles coming with raw water and developed (bacteria and other microorganisms) within the supernatant water reservoir and/or *schmutzdecke*. A pilot study of SSF at Colorado State University showed filtrate turbidity of 2.7 to 3.6 NTU for the raw water turbidity 3.4 to 4.5 NTU, which was made up of particles <1 μm in size. However, despite of low removal of turbidity, 3-log to 4-

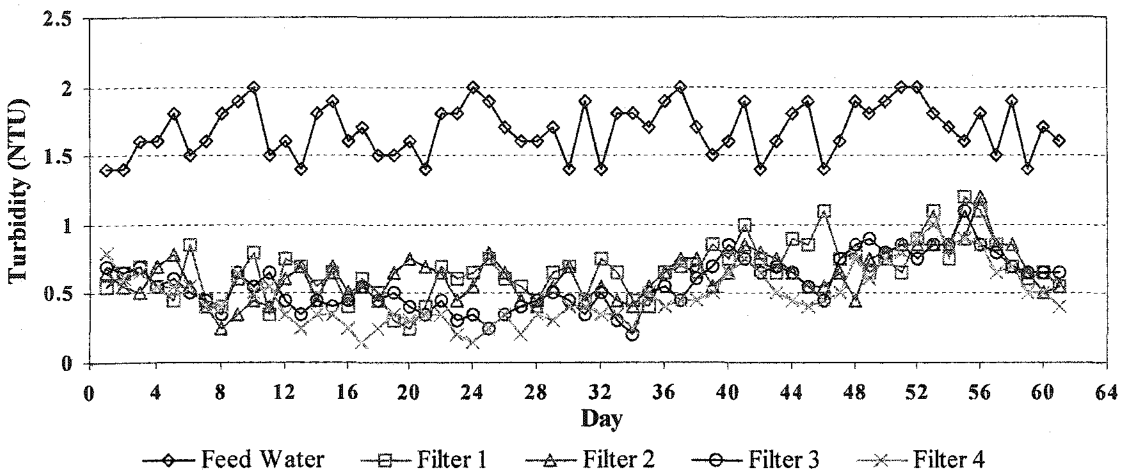



**Figure 4.25:** Feed and Final Filtrate Turbidity (Run 2)

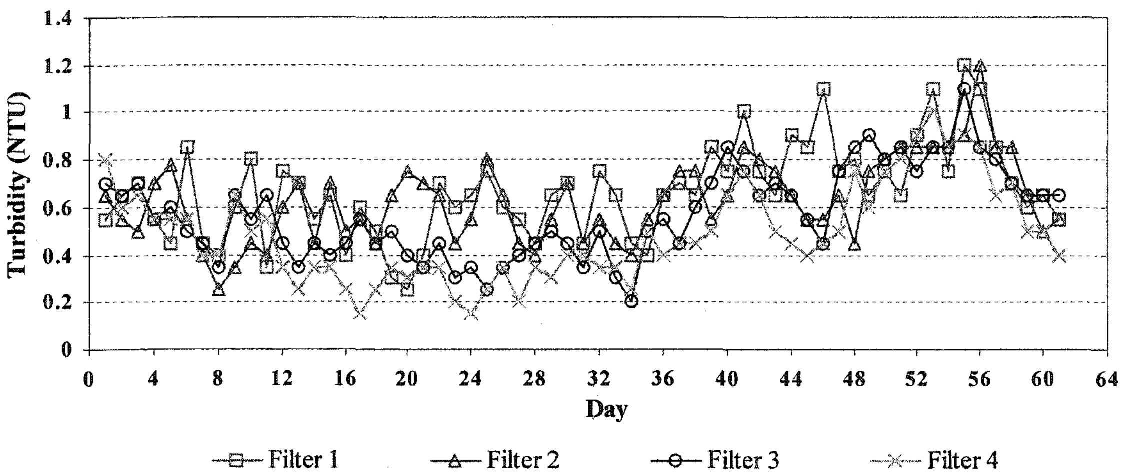



**Figure 4.26:** Final Filtrate Turbidity (Run 2)

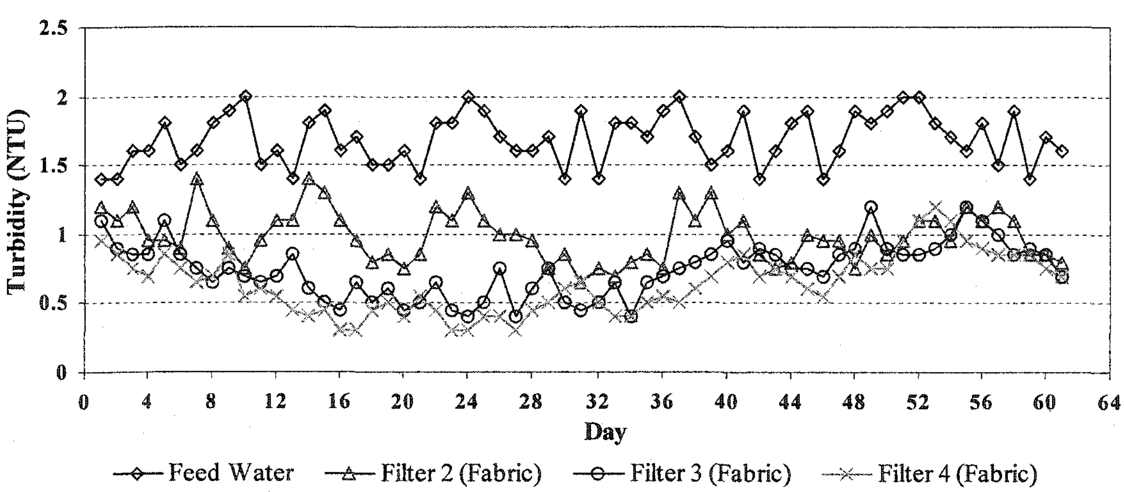



**Figure 4.27:** Feed and Filtrate after Fabric Turbidit (Run 2)

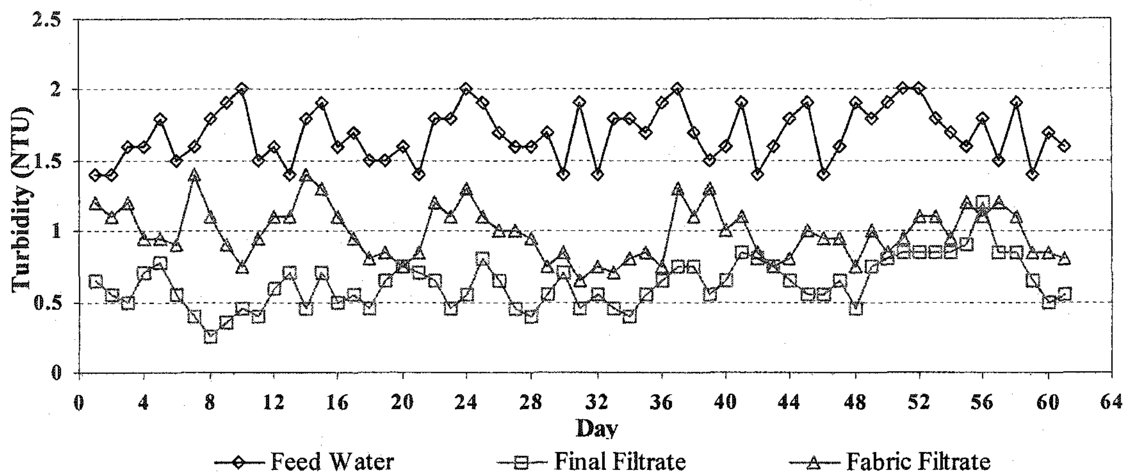



**Figure 4.28:** Feed and Filtrate Turbidity of Filter 2 (Run 2)

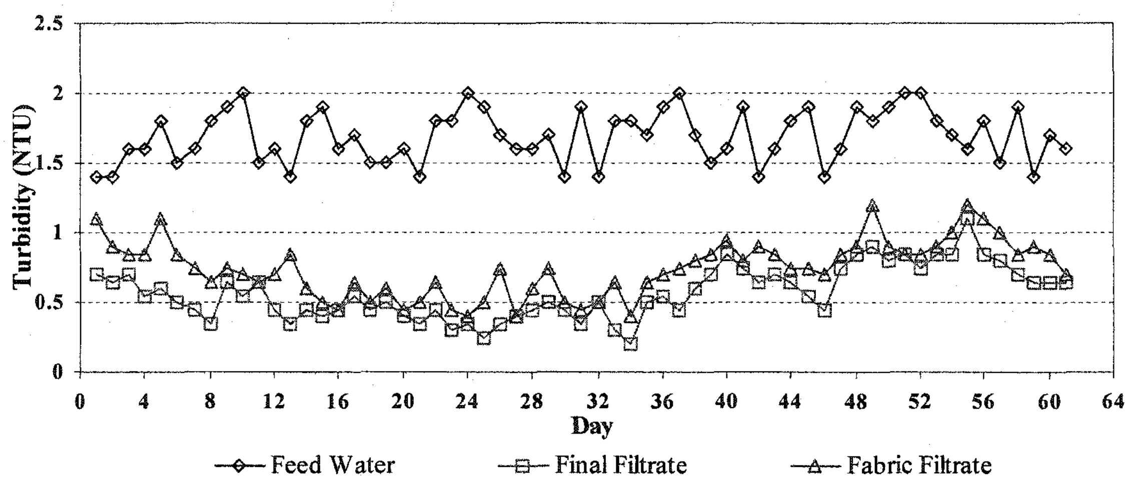



**Figure 4.29:** Feed and Filtrate Turbidity of Filter 3 (Run 2)

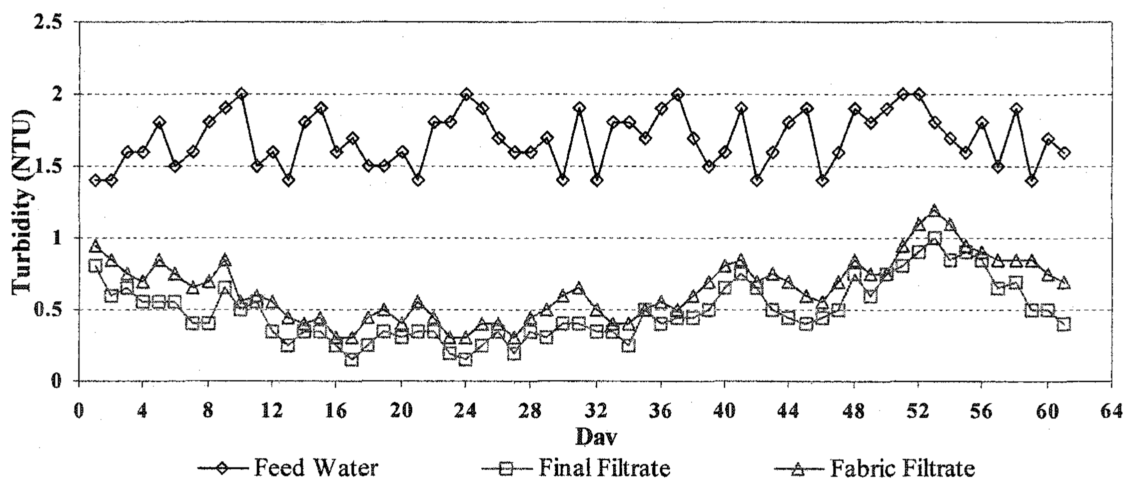



**Figure 4.30:** Feed and Filtrate Turbidity of Filter 4 (Run 2)

log removal was found for *Giardia* cysts of 10 μm size (AWWA 1991). This study helped explaining the biogrowth and escaping of higher number of smaller size microorganisms. Typically filtrate turbidity is less than 1 NTU for a mature SSF (Collins et al. 1991). The filtrate turbidity in this run was found, below the typical SSF filtrate turbidity values.

In case of the filtrates after the fabric layers, the overall average removal efficiencies were 40.9 %, 55.3 % and 61.5 % for Filters 2, 3, and 4, respectively (Table H.5).

From these observations on different filters, it is found that that thicker fabric layer along with significant bioactivity improved turbidity removal efficiency. Even though inclusion of NWF did not improve the overall turbidity removal efficiencies significantly compared to the control filter (Filter 1), the benefit of using thicker NWF was observed in capturing majority of the particles from the feed water.

#### 4.3.6.3 TOC

The daily filtrate TOC and the percentage removal efficiencies for different filters are shown in Appendix H.3 (Table H.8). The TOC in filtrates were measured on 24 different days from Day 23 to Day 60. From Table H.8 can be seen that overall average TOC removal efficiencies were 78.9 %, 79.6 %, 80.6 % and 80.6 % for the Filters 1, 2, 3 and 4, respectively. These removal values are twice the TOC removal values in Run 1 (41 % to 47 %), which might be due to the increased bioactivity and higher amount of easily degradable TOC in the raw water.

Figure 4.31 shows the feed water TOC from Day 23 to Day 60 of this filter run. Figure 4.32 shows the percentage removal of TOC in different filters, whereas Figure 4.33 shows the percentage removal of TOC across the fabric in different filters for the same period. From Figure 4.31, it can be seen that TOC removal efficiencies of control filter and filters with fabric were comparable, and the removal efficiencies increased with the time of filter operation.

For Day 0 to Day 21, the raw water TOC was within the range of 0.22 to 0.63 mg/L (average = 0.41 mg/L). During this time, the 10 days measurements of the filtrates showed the overall average TOC removal of 20 to 30%, which was typical for the TOC removal values of SSF (Collins et al. 1991). From Day 22 to Day 61, the raw water TOC was within the range of 4.35 to 9.03 mg/L (average = 6.78 mg/L), which was close to the typical surface water TOC values (range 2.5 to 9 mg/L; Graham 1999). During this time, the filtrates TOC were measured on 24 different days. From Day 23 to Day 36, the raw water TOC was decreasing from 8.53 mg/L to 5.21 mg/L, and the filtrates TOC were decreasing accordingly. While, the removal efficiencies during this time were 64.9 %, 65.3 %, 65.7 %, and 66.5 % for Filters 1, 2, 3, and 4, respectively. Even though bioactivity during that time was limited due to raw water characteristics, the increment in TOC removal indicated the presence of some bioactivity. From Day 36 to Day 39, the TOC removals increased significantly. The removals were 81.7 %, 83.1 %, 82.7 %, and 83.9 % for Filters 1, 2, 3, and 4, respectively. This increase in TOC removal at this period confirmed high bioactivity in *schmutzdecke* of the filters. At the same time, a significant biogrowth was observed on the top filter media surfaces. For the remaining period of the filter operation, the raw water TOC was high (6.89 to 8.89 mg/L, average = 7.7 mg/L). While, the TOC removals were stable (87.2 %, 88.8 %, 90.4 %, and 89.7 % for the Filters 1, 2, 3, and 4, respectively). This was due to the high consumption of glucose (easily biodegradable organic compound) by the developed biomass.

The filtrates after the fabric (Figure 4.33) shows that Filter 4 had highest, and Filter 2 had lowest TOC removal as compared to others. This indicated that higher thickness of fabric caused higher TOC removal. Even though the bioactivity was higher at the *schmutzdecke*, a significant TOC was removed in deeper portion of the fabric.

From Figures 4.31 to 4.33, it is clear that during Day 23 to Day 36, both the fabric and sand contributed to the TOC removal. After that period, fabric contributed most for the TOC removal, which indicated the high bioactivity within the fabric.

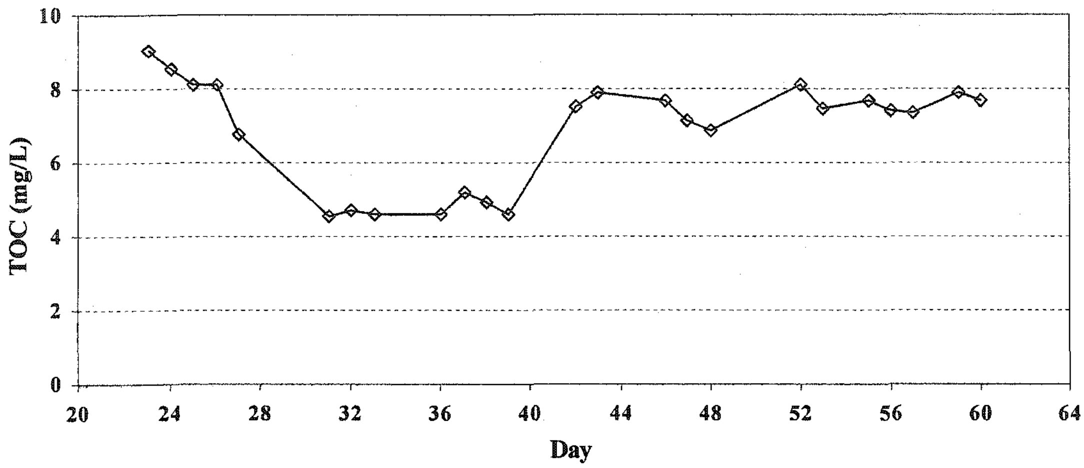



**Figure 4.31:** Feed Water TOC (Run 2)

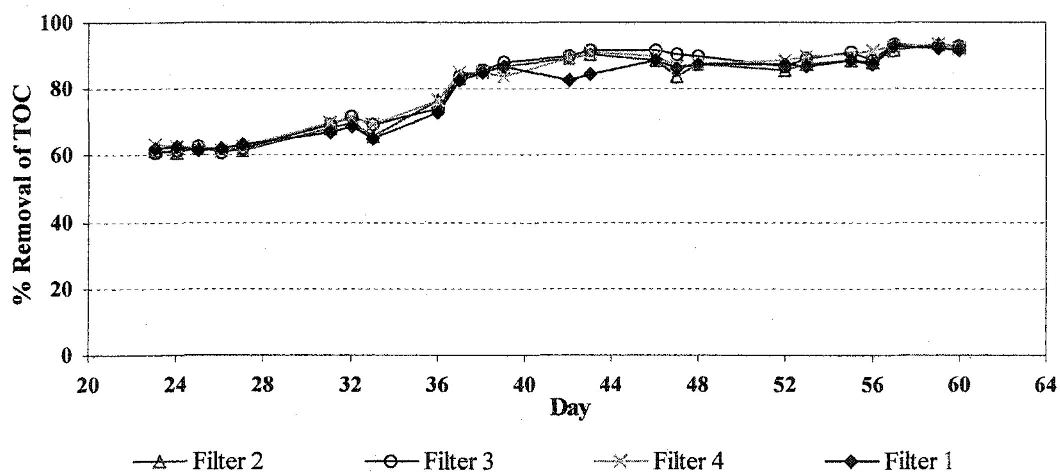



**Figure 4.32:** Percent Removal of TOC in Filters (Run 2)

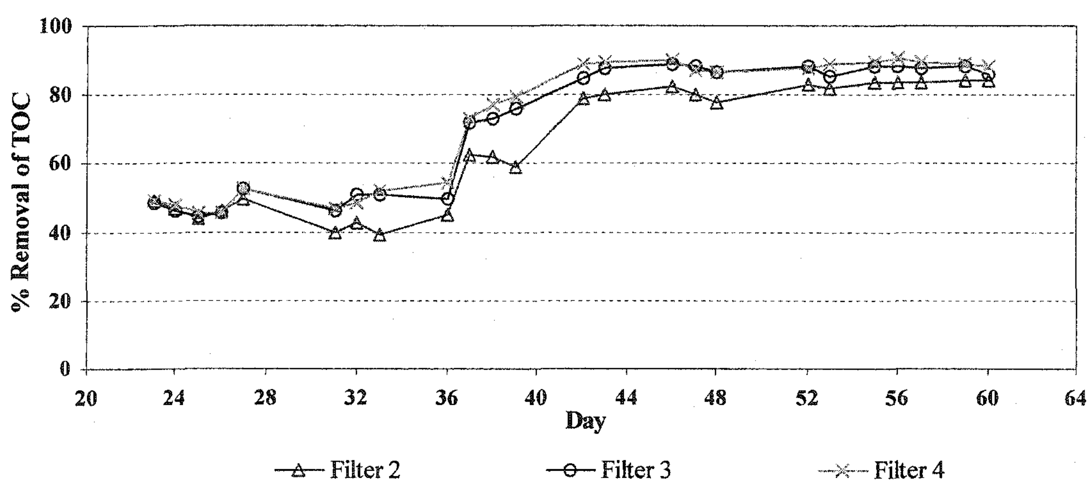



**Figure 4.33:** Percent Removal of TOC in Fabric (Run 2)

Generally, TOC removal efficiency of SSF is less than 25 % for natural surface water (Collins et al. 1991; Cleasby 1991), while Barrett and Silverstein (1988) reported 80 % of TOC removal for the simulated influent water with TOC concentration of 4.5 to 7.5 mg/L, and containing significant portion of readily utilizable carbon (glucose). The results in the present study are comparable to the results obtained by Barrett and Silverstein. Mbwette reported that POC was removed more than 90 % in the filter without fabric and with fabrics. As POC was not determined in this study, the comparison with Mbwette's study could not be shown.

#### 4.3.6.4 Nitrate and Ammonia

Table 4.11 shows the average feed water $NH_3$-N and the removal efficiencies in different filters. Table 4.12 shows the feed water $NO_3^-$-N and the concentrations in the filtrates from different filters. The detail measurements are shown in Appendix H.4 (Table H.10) for ammonia and Appendix H.5 (Table H.12) for nitrates.

**Table 4.11:** Ammonia-Nitrogen Removal Efficiencies of Filters (Run 2)
(Ammonia-Nitrogen Unit – mg/L)

| | Feed ($NH_3$-N) | % Removal | | | |
|---|---|---|---|---|---|
| | | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
| **Average*** | 0.57 | 55.6 | 54.7 | 57.7 | 57.7 |
| **Standard Deviation** | 0.17 | 21.28 | 22.52 | 21.37 | 21.95 |
| **Highest** | 0.90 | 85.7 | 88.9 | 88.9 | 88.9 |
| **Lowest** | 0.27 | 17.2 | 20.3 | 20.0 | 18.7 |

* Based on 35 samples

**Table 4.12:** Filtrates Nitrate-Nitrogen of Filters (Run 2)
(Nitrate-Nitrogen Unit – mg/L)

| | Feed ($NO_3^-$-N) | Filtrates | | | |
|---|---|---|---|---|---|
| | | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
| **Average*** | 1.53 | 0.56 | 0.56 | 0.54 | 0.56 |
| **Standard Deviation** | 0.32 | 0.26 | 0.3 | 0.27 | 0.3 |
| **Highest** | 2.1 | 1.1 | 1.2 | 1.15 | 1.21 |
| **Lowest** | 0.95 | 0.2 | 0.2 | 0.21 | 0.15 |

* * Based on 35 samples

From Table H.10 and Table 11, it is found that the filtrates ammonia concentrations were low and removal efficiencies were high during the Stage 3 and Stage 4. Decrease in filtrate nitrate and ammonia indicated the high bioactivity and nitrogen assimilation to biogrowth.

#### 4.3.6.5 Total Coliform and *E. coli*

In Run 2, treated wastewater effluent was mixed in the raw water as a source of total coliform and *E. coli,* during the full period of filter operation. For the first 35 days of filter operation total coliform and *E. coli* could not be found in the raw water after few hours of preparation, and consequently coliform was not found in the filtrates. When AC filtered was started to use for raw water preparation ($36^{th}$ day), coliform survived in the raw water and reached the filter media, which was indicated from total coliform survival tests (discussed earlier). Total coliform and *E. coli* in the filtrates were measured on 11 different days starting from $37^{th}$ day to find the removal efficiencies. On $37^{th}$ day, the total coliform removal efficiencies were 99.86 %, 99.97 %, 99.97 %, and 99.67% in the Filters 1, 2, 3, and 4, respectively, which indicated the filter ripening with respect to total coliform removal (Bellamy 1985a). Table 4.13 shows the average total coliform and *E. coli* removal efficiencies in different filters during the period of Day 36 to Day 61. The overall total coliform removal efficiencies were 99.65 %, 99.62 %, 99.67 %, and 99.71 % in Filters 1, 2, 3, and 4, respectively, which indicated the inclusion of fabric did not change the total coliform removal efficiencies with respect to the control filter. From Table 4.13, it is also found that 65 to 70 % of total coliform bacteria were removed in the fabric, while more than 89 % of *E. coli* were removed in the fabric. The detail coliform removal results are given in Appendix H.6 (Table H.14 to H.15).

**Table 4.13:** Total Coliform and *E. coli* Removal Efficiencies of Filters (Run 2)
(Number of Observations -11)

| | | Feed | Removal Efficiencies (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Filter 1 | Filter 2 | | Filter 3 | | Filter 4 | |
| | | CFU/100 mL | Total | Total | Fabric | Total | Fabric | Total | Fabric |
| Total Coliform | Average | 5885 | 99.65 | 99.62 | 66.73 | 99.67 | 67.81 | 99.71 | 69.59 |
| | Lowest | 3520 | 99.12 | 98.98 | 55.45 | 98.84 | 60.59 | 98.95 | 63.11 |
| | Highest | 10930 | 100.00 | 100.00 | 79.29 | 100.00 | 74.73 | 100.00 | 76.54 |
| *E. coli* | Average | 388 | 99.82 | 99.70 | 89.58 | 99.81 | 90.98 | 99.84 | 91.19 |
| | Lowest | 160 | 99.49 | 98.82 | 72.50 | 99.29 | 80.00 | 99.09 | 80.00 |
| | Highest | 780 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

* Feed coliform bacteria were measured 16 hours before the filtrate measurements.

Typically, more than 99 % of total coliform bacteria are removed in matured SSF (Bellamy 1985a). Similar results were found in this run. Mbwette (1989) reported the total coliform removal of more than 98 % for filters with 2, 4, and 6 layers of fabric. Therefore, the total coliform removal results of the Run 2 were comparable with Mbwette's study.

### 4.3.7 Filter Cleaning and Head Loss after Cleaning

At the end of filter Run 2, 25 mm of top sand was scraped and removed from all the filters. The top layer of fabric from Filters 2, 3, and 4 were also removed. After installing, AC filtered clean tap water was passed through the filters and head losses were recorded as shown in Table 4.14.

**Table 4.14:** Head losses after Filter Cleaning (Run 2)
(Head Loss Unit – mm)

| | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|
| Fabric | | 1 | 1 | 1 |
| Sand Bed | 43 | 20 | 22 | 22 |
| Total | 43 | 21 | 23 | 23 |

From Table 4.14, it is clear that removing top layer of fabric completely restored clean bed head losses across the fabric in different filters. It confirmed that most of the particles were captured within the top layer of the fabric. For the deeper layers, there were some captures, but due to high storage capacity the captured particles or the biogrowth could not affect the hydraulic conductivity of the fabrics significantly. However, in case of Run 1, removing one layer of fabric did not completely recover the clean bed head loss. It was due to the type of particles present in water during that run (bentonite clay).

For Filter 1, scraping of 25 mm of sand could not completely restore the clean bed head loss, which indicated some particles penetration and/or biogrowth in deeper portion of the sand bed. While, scraping same amount of sand from the filters with fabric completely restored the clean bed head loss.

## 4.4 Phase III

The main objective of this phase was to study the effect of filter cleaning, by removing one layer of fabric, on the filter behaviour of head loss development, *schmutzdecke* development, filter run time, and removal performance. In this phase, all the filters were operated for 10 days, after which the required flow rate of 0.1 m/h could not be maintained.

### 4.4.1 Influent Water Characteristics

During the filter run in this phase, lower level of turbidity was maintained in the raw water, and no bentonite clay was mixed as turbidity source. The tap water, used for the preparation of raw water, was filtered through AC filter for full period of filter operation. A summary of the raw water characteristics is shown in Table 4.15. The daily raw water characteristics are given in Appendix E (Table E.5).

**Table 4.15:** Raw Water Characteristics (Run 3)

| **Parameters** | **Average ± SD** | **Maximum** | **Minimum** | **No: of Sample** |
|---|---|---|---|---|
| Temperature, (°C) | 21.8 ± 0.4 | 22.4 | 22.1 | 11 |
| DO, (mg/L) | 9.41 ± 0.4 | 9.98 | 8.78 | 11 |
| PH | 7.06 ± 0.3 | 7.63 | 6.75 | 11 |
| Turbidity, (NTU) | 1.70 ± 0.2 | 2 | 1.4 | 11 |
| TOC, (mg/L) | 6.58 ± 1.3 | 8.12 | 4.31 | 11 |
| Nitrate-Nitrogen, (mg/L) | 0.66 ± 0.3 | 1.16 | 0.37 | 11 |
| Ammonia-Nitrogen, (mg/L) | 0.27 ± 0.1 | 0.46 | 0.13 | 11 |
| Total Coliform (CFU/100 mL) | 6710 ± 2532 | 10320 | 3380 | 5 |
| *E. coli* (CFU/100 mL) | 690 ± 391 | 1080 | 190 | 5 |
| Chlorophyll- A, (μg/L) | 3.3 ± 0.7 | 4.1 | 2.4 | 6 |

* SD – Standard deviation; No: - Number

### 4.4.2 Clean Bed Head Loss

At the end of filter Run 2, 25 mm of sand was scrapped and removed from all the filters and the top fabric layers were removed from the filters with fabric. The head losses after cleaning have already been shown in the filter cleaning section (Section 4.3.7) of phase II result and discussions.

### 4.4.3 Head Loss Development

The head loss development patterns in this phase are similar to Stage 3 head loss development patterns in Run 2. Figure 4.34 shows the total head loss developments during filter Run 3 in all the filters. After 2$^{nd}$ day, Filter 4 showed the highest total head losses and Filter 2 showed the lowest had losses. Filters 1 and 3 showed almost same total head losses. The overall filter operation time of 10 days can be divided into 3 stages (Stage 1: Day 0 to Day 5; Stage 2: Day 5 to Day 8; and Stage 3: Day 8 to Day 10) based on the head loss development patterns. During Stage 1, all the filters started to show head loss development from the 2$^{nd}$ day and, on Day 5, the head losses reached 193 mm, 166 mm, 243 mm, and 320 mm in Filters 1, 2, 3, and 4, respectively. During Stage 2, the head loss increment rates became high of 226 mm/d, 205 mm/d, 202 mm/d, and 218 mm/d in Filters 1, 2, 3, and 4, respectively. In this run, the head loss development followed the S-type head loss development pattern. Similar pattern was found in Run 1.

Figure 4.35 shows the head losses in the sand beds. In Filter 1, there was no fabric and total head loss was all contributed by sand bed. Sand beds of Filters 2, 3, and 4 showed no head loss increment. Even though Filter 2 had one layer of fabric, sand bed contributed no head loss increment. While, during Run 1 and Run 2, Filter 2 (with 2 layers of fabric) showed that the total head losses were almost equally contributed by the sand bed and fabric.

Figure 4.36 shows the comparative head losses in the different thickness of fabrics in different filters. After 2$^{nd}$ day, Filter 4 showed the highest head losses across fabric, and

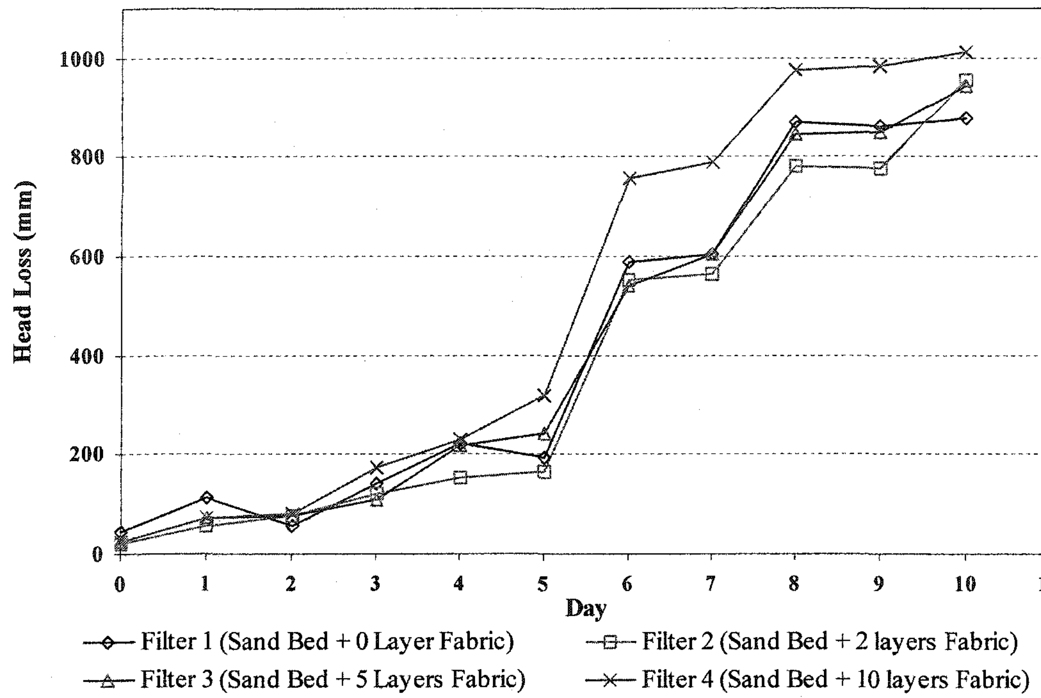



**Figure 4.34:** Comparison of Total Head Losses (Run 3)

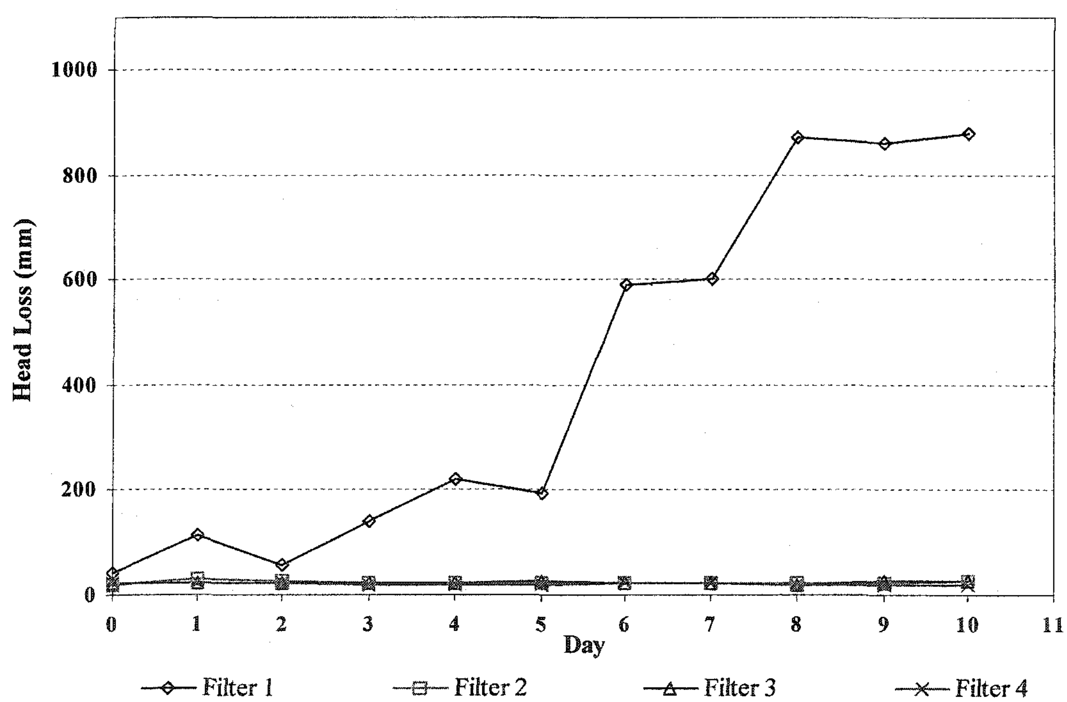



**Figure 4.35:** Comparison of Head Losses Across Sand Beds (Run 3)

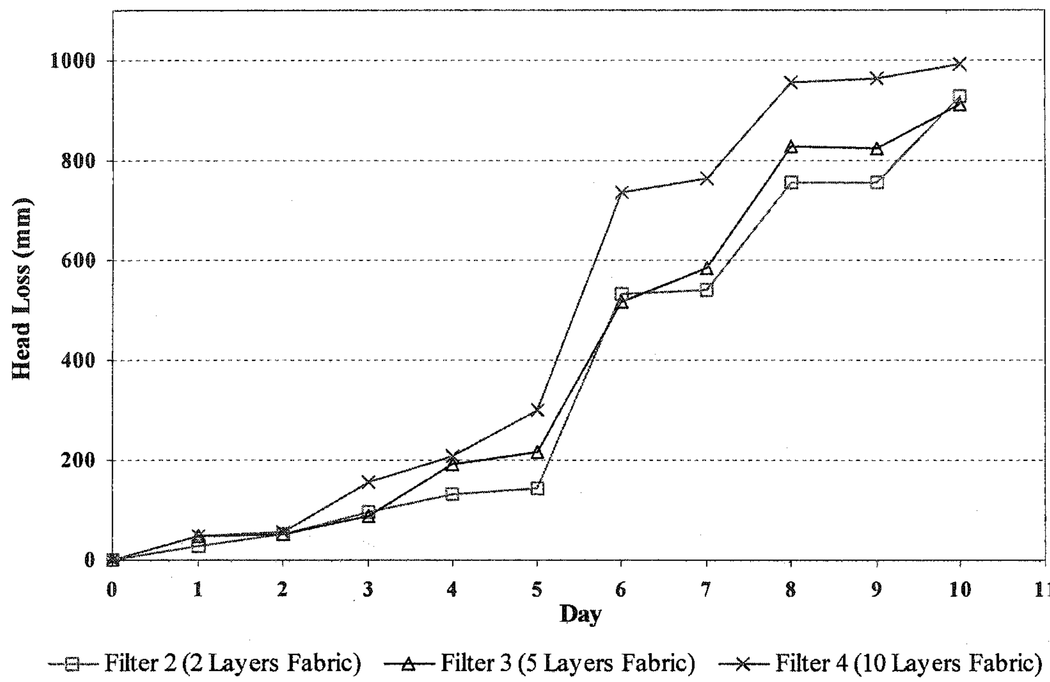



**Figure 4.36:** Comparison of Head Losses Across Fabric (Run 3)

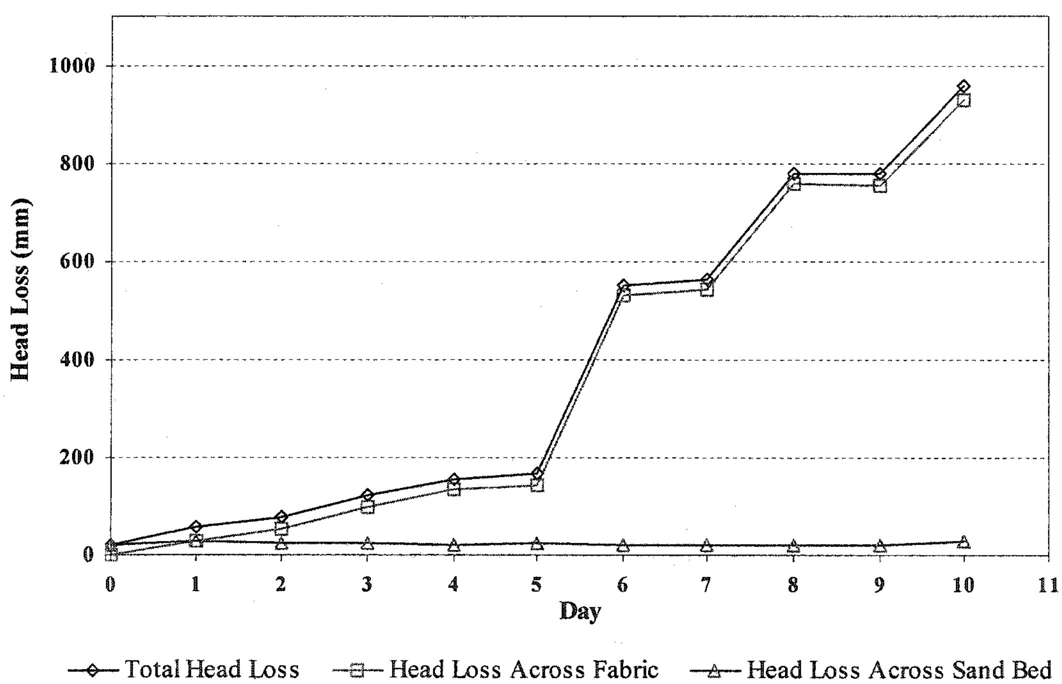



**Figure 4.37:** Head Losses in Filter 2 (Run 3)

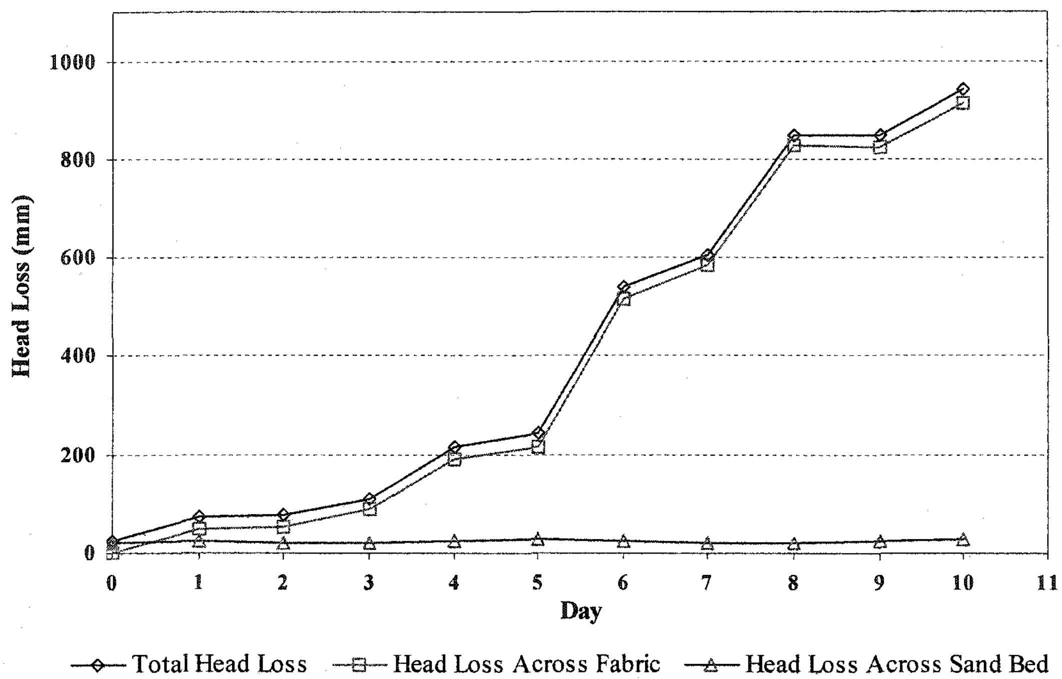



**Figure 4.38:** Head Losses in Filter 3 (Run 3)

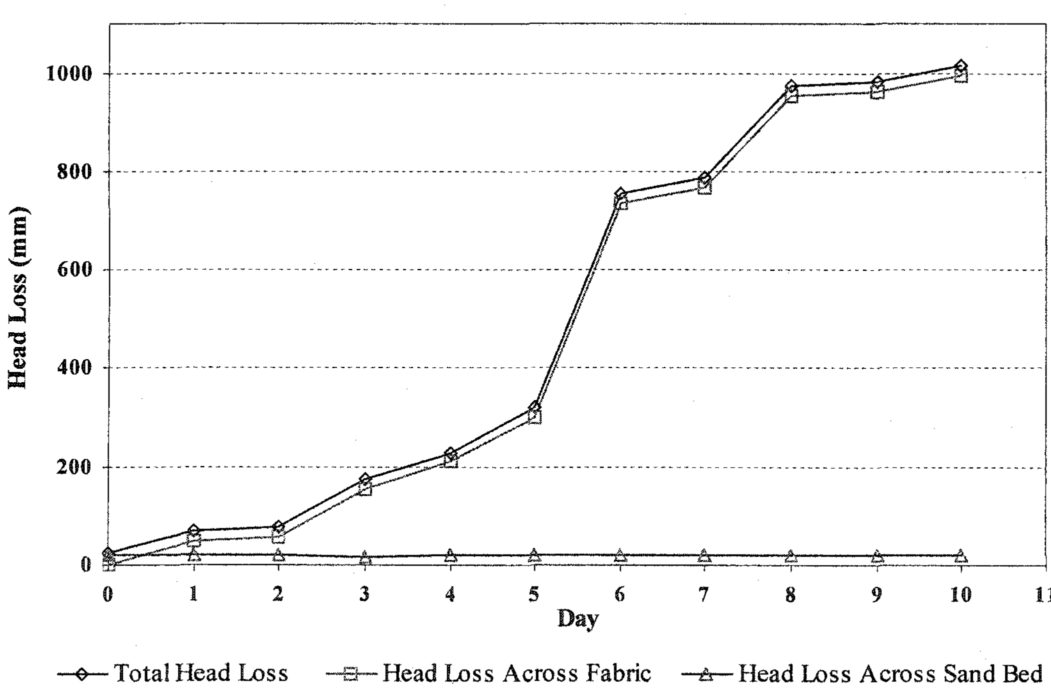



**Figure 4.39:** Head Losses in Filter 4 (Run 3)

Filter 2 showed the lowest. Figures 4.37 to 4.39 show the total head losses, head loss across fabric, and across sand beds for all the filters.

### 4.4.4 Particle Deposition and Development of *Schmutzdecke*

In this run, the raw water turbidity was low (1.4 to 2 NTU), but visible deposited/ developed layers were found on the top surface of the filter media from the 3rd day of the filter operation. *Schmutzdecke* was mainly formed by the biogrowth occurred on the filter media surfaces and settlement of the biomass developed in the feed tank or the supernatant water reservoir. The physical appearance of the *schmutzdecke* was the same as the *schmutzdecke* formed during Run 2. For the filters with fabric, no deposition or layer was visually noticed on the sand bed surface.

### 4.4.5 Filter Run Time and Sand Bed Protection Time

In Run 3, all the filters reached the maximum allowed head loss simultaneously. Therefore, inclusion of fabric did not show any increase in filter run time with respect to the control filter. Similar behaviour was found in Run 1 and 2. In this run, filter run time was 10 days for all the filters.

If 350 mm head loss was considered the end of filter run (as Mbwette considered), same filter run time was found for all the filters, which was similar to Run 1. However, Run 2 showed 1.5 times of run time increment for all the filters with fabric.

Since no deposition or growth on the sand surface of the filters with fabric was observed, the sand beds were protected from particle deposition for full period of filter operation (10 days).

### 4.4.6 Filtered Water Quality

#### 4.4.6.1 pH

The pH values of the filtrates were measured on 8 different days. Table 4.16 shows the pH of the feed and final filtrates in different filters.

**Table 4.16:** pH of Feed and Final Filtrates (Run 3)

| | Feed | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|---|
| **Average*** | 7.06 | 7.32 | 7.42 | 7.52 | 7.58 |
| **Lowest** | 6.75 | 6.78 | 7.15 | 7.31 | 7.21 |
| **Highest** | 7.63 | 7.82 | 7.92 | 7.93 | 7.84 |

* Based on 8 samples

#### 4.4.6.2 Turbidity

The turbidity of final filtrates of all the filters was always less than 0.75 NTU. The daily filtrates turbidity and the percentage removal efficiencies of different filters are shown in Appendix H.2 (Table H.6). From Table H.6 it is found that overall average turbidity removal efficiencies were 71.7 %, 72.0 %, 74.7 % and 77.0 % for Filters 1, 2, 3 and 4, respectively. The overall average final filtrate turbidity values were 0.50, 0.50, 0.45, and 0.50 NTU for Filters 1, 2, 3 and 4, respectively. These turbidity values are higher than those of filter Run 1, and lower than those of filter Run 2. In case of Run 1, the final filtrate turbidity was always less than 0.5 NTU, even though raw water turbidity was high (9.2 to 12 NTU). Whereas in case of Run 2, the raw water turbidity was same as Run 3.

Figures 4.40 to 4.42 show the feed, filtrates after fabric and final filtrate turbidity of different filters. Table 4.17 shows the average filtrates turbidity during the different stages of the filter operation.

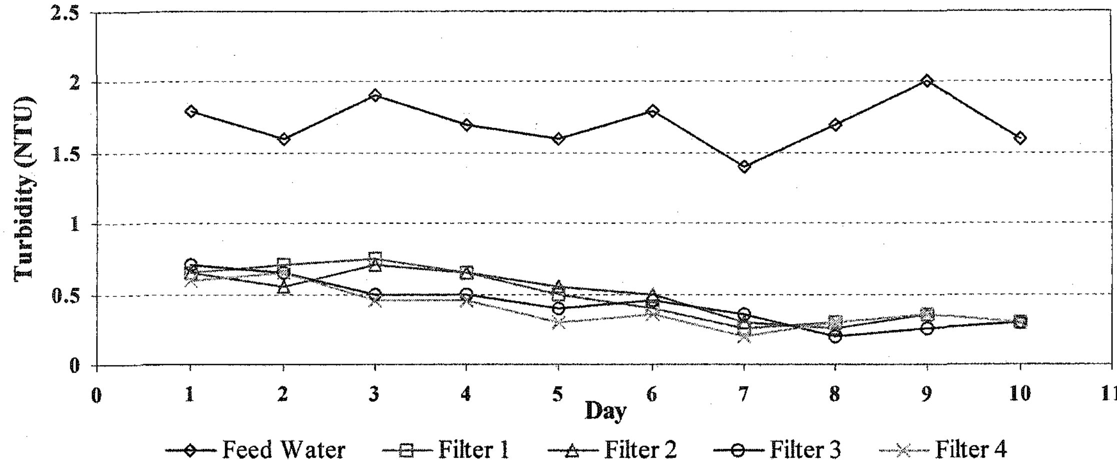



**Figure 4.40:** Feed and Final Filtrate Turbidity in all Filters (Run 3)

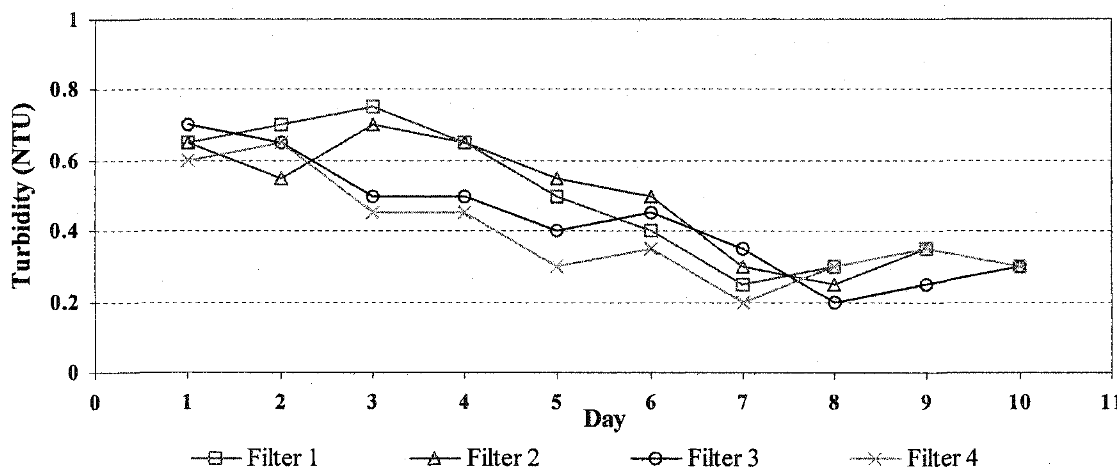



**Figure 4.41:** Final Filtrate Turbidity in all Filters (Run 3)

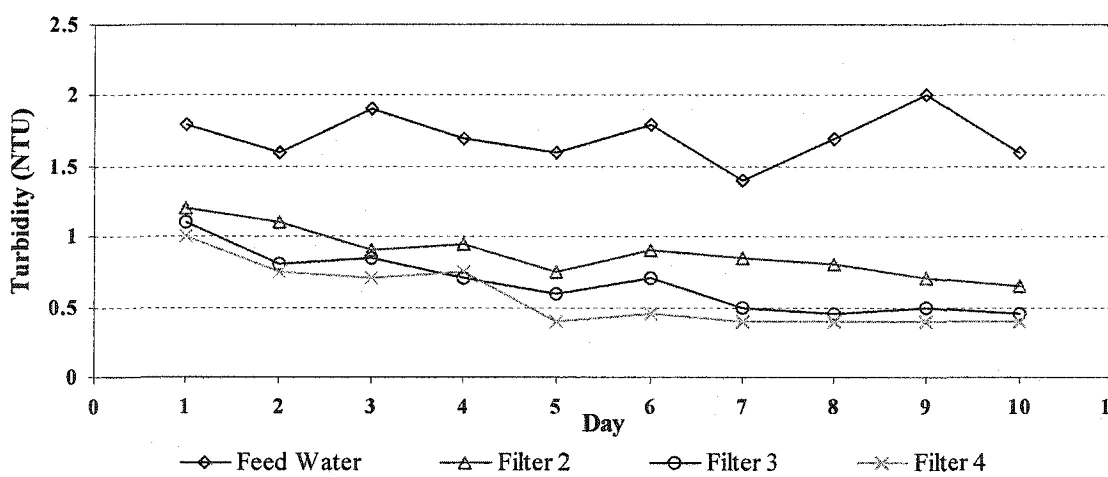



**Figure 4.42:** Feed and Filtrate after Fabric Turbidity (Run 3)

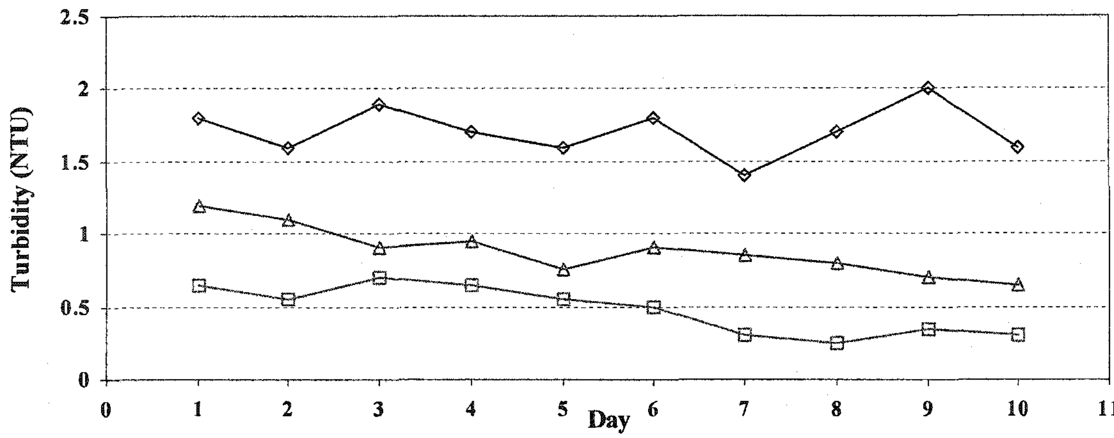



**Figure 4.43:** Turbidity of Filtrates in Filter 2 (Run 3)

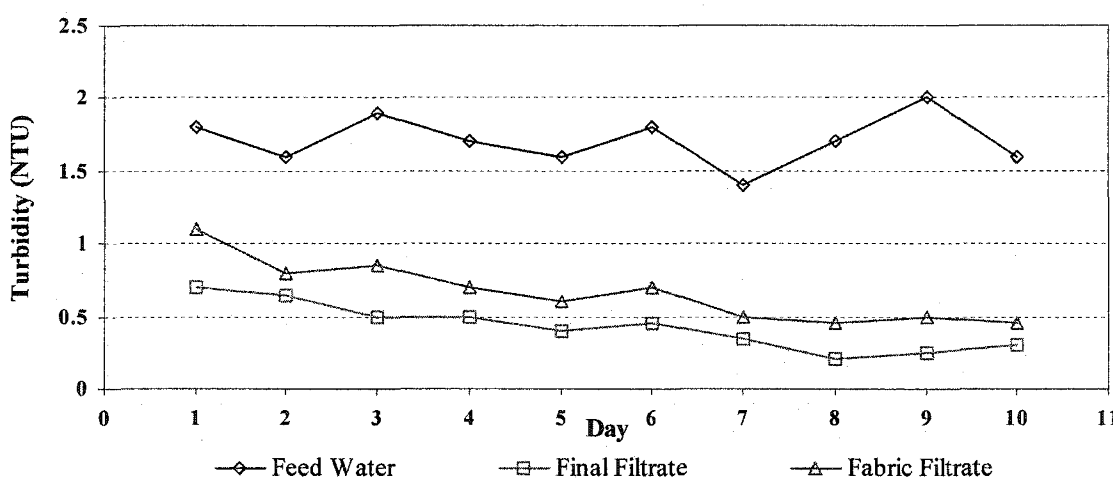



**Figure 4.44:** Turbidity of Filtrates in Filter 3 (Run 3)

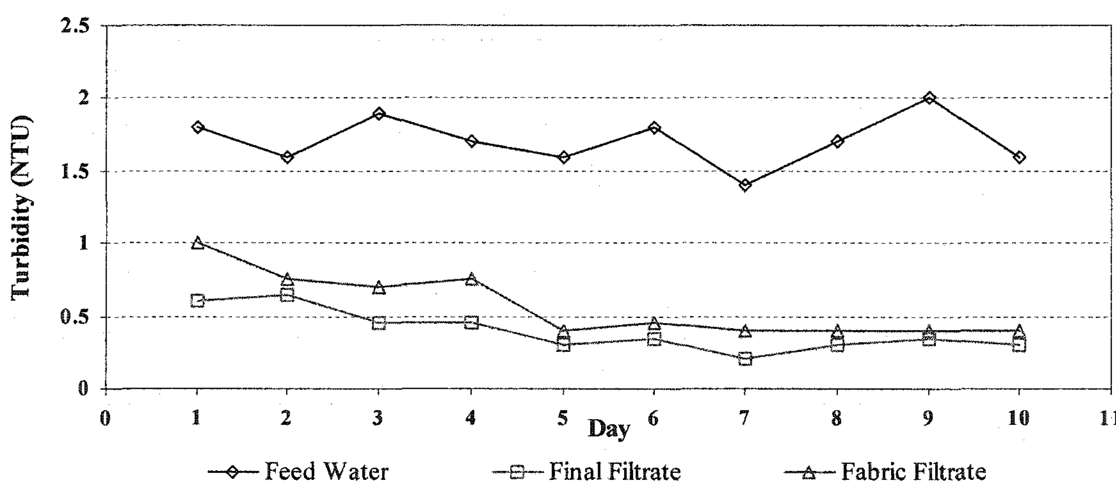



**Figure 4.45:** Turbidity of Filtrates in Filter 4 (Run 3)

**Table 4.17:** Average Turbidity of Final Filtrates at Different Stages (Run 3)
(Turbidity Unit – NTU)

| Stages | Filter 1 | Filter 2 | Filter 3 | Filter 4 |
|---|---|---|---|---|
| Stage 1 (Day 0-Day 5) | 0.65 | 0.60 | 0.55 | 0.50 |
| Stage 2 (Day 5-Day 8) | 0.35 | 0.40 | 0.35 | 0.30 |
| Stage 3 (Day 8-Day 10) | 0.30 | 0.30 | 0.25 | 0.30 |

Figure 4.40 and Table 4.17 show that filtrate turbidity decreased with time in all the filters. Figure 4.42 shows that turbidity of filtrates after fabric decreased with higher depth of fabric. Figures 4.43 to 4.45 show the feed and final filtrate turbidity in Filters 2, 3, and 4, respectively. From these figures, it is clear that major portion of the raw water turbidity was removed by the fabric.

From the above observations, it is found that that higher fabric thickness improved turbidity removal efficiency. Even though NWF did not improve the overall turbidity removal efficiencies significantly as compared to the control filter (Filter 1), the fabric captured most of the turbidity causing particles from the feed water.

#### 4.4.6.3 TOC

Figure 4.46 shows the TOC in raw water. Figures 4.47 to 4.48 show the percent removal of TOC within the entire filter bed and fabric, respectively for all the filters. The filtrates TOC were measured on 6 different days. The overall removal efficiencies were 87.2 %, 87.6 %, 90.3 %, and 91.6 % for Filters 1, 2, 3, and 4, respectively. These overall TOC removal efficiencies were higher than those of Run 2. This higher TOC removal as well as higher turbidity removal (discussed in previous section) indicated higher amount of bioactivity in the filter.

From Figures 4.46 to 4.48, it is observed that most of the TOC was removed within the fabric from the beginning of the filter operation. This indicated the presence of viable microorganisms in the remaining fabric after removing the top layer fabric at the end of Run 2. During Stage 2 and Stage 3, TOC was almost completely removed within the

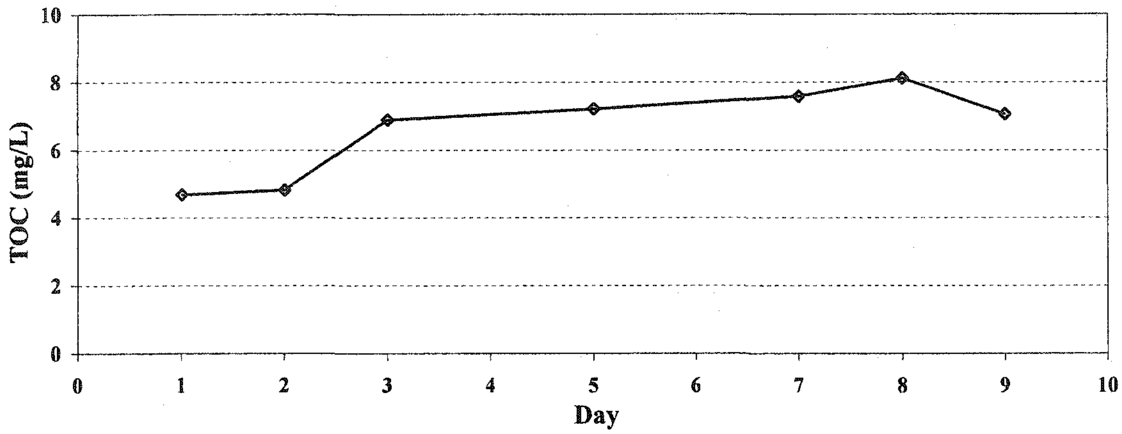



**Figure 4.46:** Feed Water TOC (Run 3)

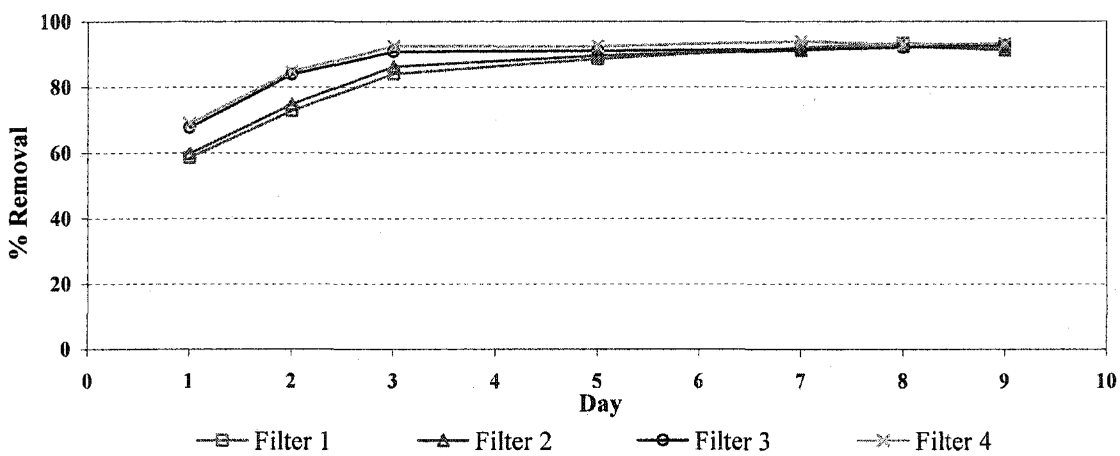



**Figure 4.47:** Percent Removal of TOC in all Filters (Run 3)

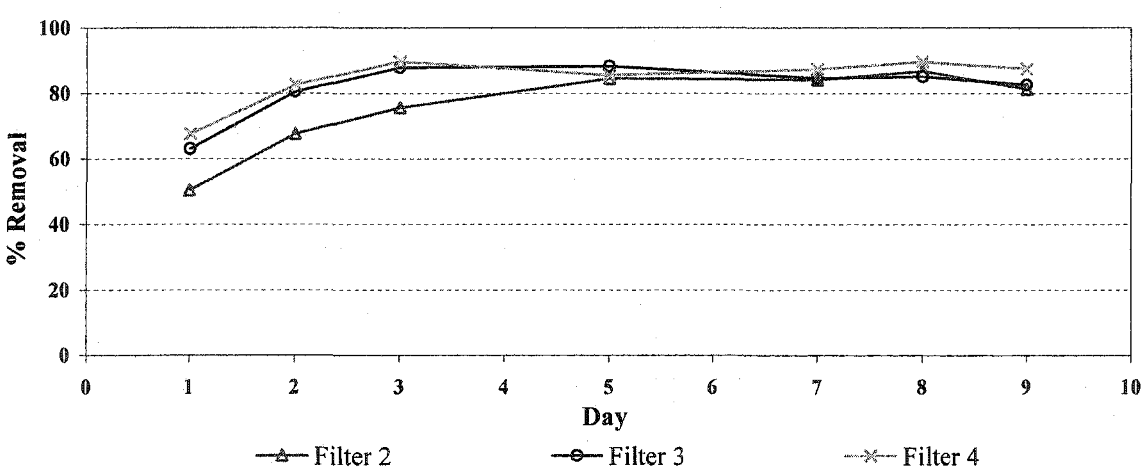



**Figure 4.48:** Percent Removal of TOC in Fabric in all filters (Run 3)

fabric. As a result, few percent (9 to 13 %) of total TOC coming in the filter was available for the sand bed below the fabric, and consequently no visible biogrowth was found on the sand surface in the filters with fabric.

#### 4.4.6.4 Nitrate and Ammonia

Table 4.18 shows the average feed water $NH_3$-N (Ammonia-Nitrogen) and the removal efficiencies in different filters. Table 4.19 shows the $NO_3^-$-N (Nitrate-Nitrogen) concentrations in the feed and final filtrates from different filters. The detail measurements are shown in Appendix H.4 (Table H.11) for ammonia and Appendix H.5 (Table H.13) for nitrates. The decrease in ammonia and nitrate in the final filtrates indicated that there were some bioactivity and nitrogen assimilation in the filters. This is also an indication of the filter ripening process.

**Table 4.18:** Ammonia-Nitrogen Removal Efficiencies of Filters (Run 3)
(Ammonia-Nitrogen Unit – mg/L)

| | **Feed ($NH_3$-N)** | **% Removal** | | | |
|---|---|---|---|---|---|
| | | **Filter 1** | **Filter 2** | **Filter 3** | **Filter 4** |
| **Average*** | 0.36 | 52.2 | 68.5 | 70.9 | 70.2 |
| **Highest** | 0.46 | 85.9 | 86.9 | 87.7 | 89.2 |
| **Lowest** | 0.28 | 33.3 | 42.8 | 49.2 | 39.7 |

* Based on 6 samples.

**Table 4.19:** Final Filtrates Nitrate- Nitrogen of Filters (Run 3)
(Nitrate-Nitrogen Unit – mg/L)

| | **Feed ($NO_3^-$-N)** | **Filtrates** | | | |
|---|---|---|---|---|---|
| | **mg/L** | **Filter 1** | **Filter 2** | **Filter 3** | **Filter 4** |
| **Average*** | 0.54 | 0.34 | 0.27 | 0.25 | 0.22 |
| **Highest** | 0.67 | 0.64 | 0.61 | 0.65 | 0.62 |
| **Lowest** | 0.37 | 0.19 | 0.10 | 0.10 | 0.10 |

* Based on 6 samples.

#### 4.4.6.5 Total Coliform and *E. coli*

Observations on total coliform and *E. coli* were done on 5 different days to find the removal efficiencies. On the 2nd day, the total coliform removal efficiencies were 97.48 %, 98.16 %, 98.82 %, and 98.99% in Filters 1, 2, 3, and 4, respectively. This indicated that the filters were ripened from the 2nd day of the filter operation. Table 4.20 shows average total coliform and *E. coli* removal efficiencies in different filters for the full filter operation. The detail total coliform and *E. coli* removal results are given in Appendix H.6 (Table H.16 to H.17).

**Table 4.20:** Total Coliform and *E. coli* Removal Efficiencies (Run 3)
(Number of Observations -5)

| | | Feed | Removal Efficiencies (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Filter 1 | Filter 2 | | Filter 3 | | Filter 4 | |
| | | CFU/100 mL | Total | Total | Fabric | Total | Fabric | Total | Fabric |
| Total Coliform | Average | 6712 | 99.20 | 99.32 | 68.59 | 99.68 | 71.43 | 99.71 | 73.98 |
| | Lowest | 3380 | 97.48 | 98.16 | 55.03 | 98.82 | 63.30 | 98.99 | 67.13 |
| | Highest | 10320 | 100.00 | 100.00 | 83.29 | 100.00 | 84.30 | 100.00 | 87.49 |
| *E. coli* | Average | 690 | 99.51 | 99.82 | 93.13 | 99.73 | 93.09 | 99.86 | 95.58 |
| | Lowest | 190 | 98.89 | 99.47 | 80.19 | 98.95 | 82.59 | 99.47 | 85.74 |
| | Highest | 1080 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

* Feed coliform bacteria were measured 16 hours before the filtrate measurements.

From the Table 4.20, it is observed that the removals of total coliform and *E. coli* in filter without fabric and filters with fabric were comparable. In case of filters with fabric, fabric contributed for major portion of total coliform and *E. coli* and the amount of removals increased with fabric depth. This indicated that, even though the top layer of fabric removed major portion of coliform, the following layers also had some contribution in coliform removals.

### 4.4.7 Fabric Cleaning and Head Loss after Cleaning

At the end of filter Run 3, all the fabric layers were removed and washed by soaking them in the water, and by applying water flow with moderate pressure from the reverse side of the fabric. The cleaned fabric layers were placed in the filters again and clean tap water was passed through to determine the head loss across fabric after cleaning. In all cases no head loss was found across the cleaned fabric, which confirmed proper cleaning of the fabric. Some particles might be still present within the fabric, but due to high storage capacity of fabric, it did not affect the head loss. Thus, the cleaning of the fabric layer by pressurized tap water was not difficult and removed most of the trapped particles.

### 4.5 Summary

The results and discussions on three different phases of the experiments can be summarized as described in the following sub sections.

### 4.5.1 Effect of Fabric and Fabric Thickness

***Capturing Particles***

The selected NWF with certain thickness (>5 layers, 22.3 mm) in this study was effective in capturing most of the particles coming to the filters, and increased sand bed protection time. Two layers (8.9 mm thick) of the NWF was capable of capturing particles during the initial stages of the filter runs. After a certain period (5 days in Run 1, 36 days in Run 2) two layers of fabric allowed particles to pass through and deposit on sand bed and, thus, it was not suitable protecting filter sand bed. Five layers of fabric (22.3 mm) captured most of the particles for comparatively longer period (11 days in Run 1, 48 days in Run 2), and it also showed similar head loss development trend as ten layers of fabric (44.5 mm) showed. Thus five layers of NWF was adequate for protecting the filer sand bed.

In Run 1, the average turbidity removals were 74.4 %, 96.1 %, and 98.0 % within 2, 5, and 10 layers of fabric, thus, the fabric could be credited for capturing most of the particles within the size range of 2.7 μm (10 % passing size) to 7 μm (90 % passing size). It is clear that the 5 layers fabric's turbidity removal credit was close to that of 10 layers fabric. Thus, it confirmed the adequacy of five layers of fabric in protecting sand bed. Mbwette (1989) reported that 6 layers (21.6 mm) of NWF of 14, 430 $m^2/m^3$ of specific surface area showed good protection (78 to 95 % turbidity removal) against particles (size range of 4 to 64 μm) escaping, which is agreeable with the present study. Besides, in the present study, the size range of the particles was in the lower range as compared to the study by Mbwette.

***Operational Improvements***

As the addition of NWF on sand bed showed protection against particles deposition on sand bed, the use of appropriate thickness (>22.3 mm) of NWF indicated that the filter cleaning without sand bed scraping and disturbing was possible. Removing fabric from the filter seemed to be easier and quicker than the sand scraping, which would provide shorter filter down time during cleaning. Removing one layer fabric also resulted rapid filter ripening (<2 days) due to the presence of active biomass within the fabric. Moreover, the removed fabric also showed easy washability and complete restoration of clean bed head losses. These observations could have the practical implication of developing filter cleaning scheme for multi layered NWF aided SSF. For instance, if a filter was started with 10 layers of fabric, removing 1 layer at the end of each filter run would give 5 consecutive easy filter cleaning operations, and after 5 cleaning operations the previously removed and cleaned fabric could be placed at the bottom of remaining fabric layers for the subsequent filter run, and again the filter could be started with 10 layers of fabric. This could be continued until the sand bed showed significant particles deposition and head loss development. Even though addition of NWF would increase the initial cost, the over all operational cost expected to decrease.

***Water Quality Improvements***

The conventional SSF is generally considered to be an effective treatment process for the surface waters and highly credited for removal of turbidity, coliform, cysts, TOC, and other contaminants. While, the results of the three filter runs in the present study showed that inclusion of NWF increased the filtrate water quality, as compared to the control filter (filter without fabric). For example, in the filter Run 1, the overall average turbidity of filtrates were 0.20, 0.15, 0.15, and 0.15 NTU for the Filters 1, 2, 3, and 4, respectively, and in the filter Run 2, these values were 0.65, 0.65, 0.55, and 0.50 NTU, respectively. The TOC and ammonia-nitrogen removals in Run 2 and Run 3 also showed similar trends. Even though the improvement in water quality is marginal, significant portion of impurities removal within fabric indicate that adequate depth of fabric can work as a integrated part of conventional SSF.

### 4.5.2 Effect of TOC

During Run1 and a part of Run 2, TOC in the raw water was low (<1 mg/L). The bioactivity during that period was also found less pronounced, which was indicated by lower removal performance and *schmutzdecke* development. During the filter Run 2 and Run 3, it was found that high amount of nutrient (TOC ~ 4.5 to 9 mg/L) along with suitable environment (temperature and non toxic effect of raw water) in the raw water increased the bioactivity and caused rapid filter ripening in all the filters. Since surface water TOC typically varies within the range of 2.5 to 9 mg/L (Graham 1999), the TOC in Run 2 and Run 3 can be considered as high. However, this high TOC was also responsible for shorter filter run time (10 days) in Run 3 for all the filters. Even though high nutrient shortened the filter run, easily biodegradable TOC can be artificially increased in the raw water for initial few days to enhance the filter ripening time.

### 4.5.3 Effect of Turbidity and Particle Size

Generally, high turbid water causes shorter filter run in SSF, and this was found in filter Run 1. While, even though the raw water turbidity was low (1.4 to 2 NTU) during filter Run 2 and Run 3, the filter runs were shortened due to the rapid bigrowth in the all filters. Run 1 produced lower turbidity water with higher raw water turbidity (9.5 to 12 NTU). While, Run 2 and Run 3 produced higher turbidity filtrate with lower turbidity raw water. This was due to the sizes and types of particles dominating in raw waters in different runs. In Run 1, turbidity was mainly caused by bentonite clay (90 % of the particles were larger than 2.7 μm) and the biogrowth was limited by the raw water characteristics. On the other hand, during a part of Run 2, and Run 3, clay was not added and biogrowth was also enhanced. Schuler et al. (1991) reported that a SSF with 0.27 mm ES and 0.15 m/h filtration rate effectively removed particles larger than 3 μm and the majority of the filtrate turbidity was due to the presence of the particles smaller than 3 μm. Similarly, in the present study, during Run 1, most of the particles were captured by the filters and thus filtrate turbidity was less. While, in Run 2 and Run 3, smaller microorganisms were grown in the *schmutzdecke* and/or supernatant water reservoir of the filters, which were mainly bacteria (size < 3 μm), escaped the filtration and consequently caused comparatively higher turbidity in the filtrate.

# Chapter V

# CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

In this study, NWF was used on the sand bed of SSF to evaluate its operational and water treatment performance. The laboratory experiments were conducted in three different phases. Based on the laboratory studies conducted, the following conclusions are drawn:

### Phase – I

- No significant difference in overall filter run time was found for the SSF with NWF as compared to SSF without NWF.
- Solids capturing by fabric layers proceeded sequentially. Virtually all the incoming solids were captured by a fabric layer during a certain period and after that, particles propagated to the next layer.
- NWF significantly enhanced the protection time for sand bed. The sand bed protection time varied linearly with fabric depth.
- Water treatment performances (turbidity and TOC removals) of SSF with fabric were comparable to the SSF without fabric and were in accordance with those available in literature.

### Phase – II

- Lower influent water turbidity prolonged the filter run time. No significant difference was found in the overall filter run time for SSF with NWF and without NWF.
- NWF significantly enhanced the run time for sand beds.
- Higher amount of TOC along with non-toxic affect of influent water significantly increased the bioactivity and enhanced the filter ripening.

- NWF provided a good support for the biological growth and contributed to a significant portion of TOC (>60 %), ammonia-nitrogen (>40 %), and total coliform (>66 %) removals.
- Total coliform and *E. coli* removal performances of SSF with fabric were comparable to the SSF without fabric. In all the cases, removal performances were more than 99 %.

**Phase – III**

- No significant difference in overall filter run time was found in SSF with and without NWF.
- NWF protected the sand beds for the entire filter run.
- Residual active biomass in the fabric layer (after removing top fabric layer) helped short filter ripening period of <2 days.
- Excessive amount of bioactivity, in the sand for the filter without fabric, and in the fabric for the filters with fabric shortened the filter run time.
- Removal performances were comparable for filter with and without NWF.
- Cleaning of fabric in laboratory by pressurized tap water was easy and entirely restored the clean bed head loss in the fabric.

**Summary**

To summarize, the use of five layers (22.3 mm) of selected NWF demonstrated to be capable enough of capturing the particles and protecting the sand bed for longer period. Even though inclusion of NWF did not show any significant increment in filter run time, an appropriate thickness of NWF could provide non sand-bed disturbing filter cleaning. NWF allowed a good support for biogrowth and allowed *schmutzdecke* development on it. Fabric contributed to the majority of the impurities removal. Pollutants removal performances of SSF with NWF were comparable with SSF without NWF. The raw water characteristics such as TOC and turbidity affected the filter performance significantly. High TOC in raw water enhanced the filter ripening and high turbidity shortened the filter run time. The cleaning of filter by removing fabric layers and washing fabric layers demonstrated to be convenient.

## 5.2 Recommendations

1. Particle size analysis of the feed and filtrates along with the turbidity are recommended, which would give more insight of the particle capturing behaviour of the NWF.

2. Pilot scale experiments should be conducted with natural surface water in order to find the performance of NWF in SSF.

3. Complete filter operation is required (for the filter started with higher number of fabric layers) to develop a filter-cleaning scheme by removing top few (one/more) layers of fabric (without removing sand) at the end of each filter run.

4. Since variable filtration rate is convenient for small water systems in developing countries, laboratory or pilot experiments should be conducted by using variable filtration rate.

5. Experiments should be conducted to find suitable method for fabric cleaning for large SSF.

6. The used tap water (from 235 Essex Hall, University of Windsor) should be investigated to find the unknown toxicity which was limiting the biogrowth.

7. Cost benefit analysis for using NWF in SSF should be performed.

## REFERENCES


APHA, AWWA and WEF (1998). *Standard Methods for the Examination of Water and Wastewater, 20th Edition.* American Public Health Association, Washington, D. C., U. S. A.

AWWA (1991). *Manual of Design for Slow Sand Filtration*; Hendricks , D. (ed.), Barrett, J. M., Bryck, J., Collins, M. R., Janonis, B. A. and Logsdon, G. S., AWWA research Foundation and American Water Works Association, Colorado, U. S. A.

Baker, M. N. (1949). *The Quest for Pure Water.* American Water Works Association, New York, U. S. A.

Barret, J.M. and Silverstein, J. (1988). The Effects of High Carbon and High Coliform feed Waters on the Performance of Slow Sand Filters under Tropical Conditions, Chapter 4, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology;* Graham, N. J. D. (ed.). Ellis Horwood Ltd, Chichester; John Wiley & Sons, New York, 231-252.

Bellamy W. D., Hendricks D. W. and Logsdon G. S. (1985a). Slow Sand Filtration: Influences of Selected Process Variables. *Journal of American Water Works Association,* **77**(12), 62-66.

Bellamy, W. D., Silverman, G. P. and Hendricks, D. W. (1985b). Removing *Giardia* cysts with Slow Sand Filtration. *Journal of American Water Works Association,* **77**(2), 52-60.

Bellinger, E. T. (1979). Some Biological Aspects of Slow Sand Filters. *Journal of the Institute for Water Engineers and Scientists,* **33**, 19-29.

Bowles, D. A., Drew, W. M. and Hirth, G. (1983). The Application of Slow Sand Filtration Process to the Treatment of Small Town Water Supplies. Paper presented at the *Annual Convention of the Australian Water and Wastewater Association,* Sydney.

Bryck, J. (1987). *Giardia* Removal by Slow Sand Filtration-Pilot to Full Scale. Paper Presented at Sunday Seminar on Coagulation and Filtration: Pilot to Full Scale, *American Water Works Association Annual Conference,* June 14, Kansas City.

Burman, N. P. (1961). Bacteriological Control of Slow Sand Filtration. *Effluent and Water Treatment Journal,* **2**, 674-677.

Burman, N. P. and Lewin, J. (1961). Microbiological and Operational Investigations of Relative Effects of Skimming and in Situ Sand Washing on two Experimental Sand Filters. *Journal of the Institute for Water Engineers,* **15**(5), 355-367.

Cleasby, J. L. (1991). Source Water Quality and Pretreatment Options for Slow Sand Filters, Chapter 3, in: *Slow Sand Filtration*; Logsdon, G. S. (ed.). American Society of Civil Engineers, New York, 69-100.

Cleasby, J. L. Hilmoe, D. J. and Dimitracopoulos, C. J. (1984). Slow Sand and Direct in-line Filtration of a Surface Water. *Journal of American Water Works Association,* **76**(12), 44-55.

Collins, M. R. and Eighmy, T. T. (1988). Modifications to the Slow Sand Filtration Process for Improved Trihalomethane Precursor Removal, Chapter 4, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Ltd., Chichester; John Wiley & Sons, New York, 281-304.

Collins, M. R., Eighmy, T. T. and Malley, Jr. J. P. (1991). Evaluating Modifications to Slow Sand Filters. *Journal of American Water Works Association,* **83**(9), 62-70.

Collins, M. R., Eighmy, T. T. and Malley, Jr. J. P. (1990). Modifications to Enhance the Performance of Conventional Slow Sand Filtration. Paper Presented at *Emerging Technologies in Practices Seminar*. American Water Works Association National Conference, June 1990, Cincinnati, Ohio.

Cook, G. J. (1984). *A Handbook of Textile Fibres Man-made Fibres. 5th ed.*, Marrow Publishing Company, U. K.

Cullen, T. R. and Letterman, R. D. (1985). The Effect of Slow Sand Filter maintenance on Water Quality. *Journal of American Water Works Association,* **77**(12), 48-55.

Davis, E. M. and Gloyna, E. F. (1970). Bactericidal Effects of Algae on Enteric Organisms. *Technical Report EHE-70-06/CRWR-55,* Department of Civil Engineering, University of Texas, Austin.

Duncan A. (1988). The Ecology of Slow Sand Filters, Chapter 3, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Ltd, Chichester; John Wiley & Sons, New York, 163-180.

Ellis K.V. (1987). Slow Sand Filtration. WEDC *Journal of Developing World Water*, **2**, 196-198.

Ellis K. V. (1985a). Slow Sand Filtration. *CRC Critical Reviews in Environmental Control,* **15**(4), 315-354.

Ellis, K. V. (1985b). Slow Sand Filtration as a Technique for the Tertiary Treatment of Municipal Sewages. *Water Research,* **121**(4), 403-410.

Faust, S. D. and Aly, O. M. (1999). *Chemistry for Water Treatment, 2nd (ed.).* Lewis Publishers, Washington, D. C., U. S. A.

Fletcher, E. A. (1979). Needled Filter Media for Solid/Liquid Separation. *Proceedings of 2nd World Filtration Congress,* London.

Fox, K. R. (1996). Waterborne Disease Outbreaks and Small Systems. *Journal of American Water Works Association,* **88**(9), 8.

Fox, K. R. and Lytle, D. A. (1996). The Cryptosporidiosis Outbreak in Milwaukee: Investigations and Recommendations. *Journal of American Water Works Association,* **88**(9).

Fox, K. R., Miltner, R. J., Logsdon, G. S., Dicks, D. L. and Drolet, L. F. (1984). Pilot Plant Studies of Slow-rate Filtration. *Journal of American Water Works Association,* **76**(12), 62-68.

Gemeson, A. L. H. and Saxon, J. R. (1967). Field Studies on the Effect of Daylight on Mortality of Coliform bacteria. *Water Research,* **1**, 279-295.

Giroud, J. P. (1985). *Geotextiles and Geomembranes Definitions, Properties and Design: Selected Papers, Revisions and Comments (2nd ed.).* Industrial Fabrics Association International, Minnesota, U.S.A.

Graham, N. J. D. (1999). Removal of Humic Substances by Oxidation/Biofiltration Processes – a Review. *Water Science and Technology*, **40**(9), 141-148.

Graham, N. J. D. (ed.) (1988). *Slow Sand Filtration: Recent Developments in Water Treatment Technology*, Ellis Horwood, Ltd., Chichester; John Wiley & Sons, New York.

Graham, N. J. D, and Collins, M. R. (eds.) (1996). *Advances in Slow Sand and Alternative Biological Filtration.* John Wiley & Sons, Chichester, U. K.

Graham, N. J. D. and Mbwette, T. S. A. (1991). Protected Slow Sand Filtration: Specification of Non-Woven Synthetic Fabric Layers. *Water Supply*, **9**, 157-164.

Graham, N. J .D., Clarke, B. A, Jones, C. J. and Lloyd, B. J. (1996). Effect of Reduced Depth, Fabric-Protected Slow Sand Filters on Treated Water Quality, Part IV, in: *Advances in Slow Sand and Alternative Biological Filtration*; Graham, N. J .D. and Collins, M. R. (eds.). John Wiley & Sons, Chichester,U. K., 233-244.

Greaves, G. F., Grundy, P. G. and Taylor, G. S. (1988). Ozonation and Slow Sand Filtration for the Treatment of Coloured Upland Waters-pilot Plant Investigations, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Ltd, Chichester; John Wiley & Sons, New York, 153-162.

Haarhoff, J. and Cleasby, J. L. (1991). Bilogical and Physical Mechanisms in Slow Sand Filtration, Chapter 2, in: *Slow Sand Filtration*; Logsdon, G. S. (ed.). American Society of Civil Engineers, New York, 19-68.

Happel, J. (1959). Viscous flow relative to arrays of cylinders. *AIChE Journal,* **5**(2), 174-177.

Hendel, B., Marxsen, J., Fiebig, D. and Preuss, G. (2001). Extracellular Enzyme Activities During Slow Sand Filtration in a Water Recharge Plant. *Water Research*, **35**(10), 2484-2488.

Hendricks, D. W. (ed.) (1988a). Filtration of *Giardia* Cysts and Other Particles Under Treatment Plant Conditions. *Research Report on Water Treatment and Operations*. Denver: AWWA Research Foundation, February.

Hendricks, D. W. (1988b). Roundtable: Slow Sand Filtration. *Journal of American Water Works Association,* **80**(12), 12-19.

Hendricks, D. W. and Bellamy, W. D. (1991). Microorganisms Removal by Slow Sand Filtrations, Chapter 4, in: *Slow Sand Filtration*; Logsdon, G. S. (ed.). American Society of Civil Engineers, New York, 101-121.

Huisman, L. (1978). Developments of Village Scale Slow Sand Filtration. *Progress in Water Technology,* **11**(1/2), 159-165.

Huisman, L. and Wood, W. E. (1974). *Slow Sand Filtration.* World Health Organization, Geneva.

Klein, H. P. and Berger, C. (1994). Slow Sand Filters Covered by Geotextiles. *Water Supply, Zurich*, **12**(3/4), 221-230.

Leland, D. E. and Damewood III, M. (1990). Slow Sand Filtration in Small Systems in Oregon. *Journal of American Water Works Association,* June 1990, 50-59.

Letterman, R. D. (1991). Operation and Maintenance, Chapter 6, in: *Slow Sand Filtration*; Logsdon, G. S. (ed.). American Society of Civil Engineers, New York, 149-164.

Lloyd, B., Pardan, M. and Wheeler, D. (1983). Process Aids for Slow Sand Filtration. *Waterlines,* **24**.

Logsdon, G. S., Khone, R., Abel, S. and Labonde, S. (2002). Slow Sand Filtration for Small Water Systems. *Journal of Environmental Engineering and Science*, **1**, 339-348.

Logsdon, G. S. (1991a). Filtration Operation and Maintenance for Small Systems. *Proceedings of AWWA Annual Conference on Resources, Engineering and Operations for the New Decade*, 601-618.

Logsdon, G. S. (ed.) (1991b). *Slow Sand Filtration.* American Society of Civil Engineers, New York.

Logsdon, G. S. and Fox, K. R. (1988). Slow Sand Filtration in the United States, Chapter 1, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology,* Graham, N. J. D. (ed.). Ellis Horwood Ltd., Chichester, John Wiley & Sons, New York, 29-46.

Lunenschloss, J. and Albrecht, W. (1985). *Non-Woven Bonded Fabrics*. Ellis Horwood Limited, Chichester, England.

Mbwette, T. A. S. (1989). *The Performance of Fabric Protected Slow Sand Filters*. PhD Thesis. Department of Civil Engineering, Imperial College of Science, Technology and Medicine, London, U. K.

Mbwette, T. S. A. and Graham, N. J. D. (1988). Pilot Plant Evaluation of Fabric Protected Slow Sand Filters, Chapter 5, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed). Ellis Horwood Ltd, Chichester; John Wiley & Sons, New York, 305-330.

McConnell, L. K., Sims, R. C. and Barnett, B. B. (1984). Reovirus Removal and Inactivation by Slow-rate Sand Filtration. *Applied Environmental Microbiology,* **48**(4), 818-825.

McDonald, M. (1971). *Non-Woven Fabric Technology*. Noyes Data Corporation. New Jersey, U. S. A.

McNair, D. R., Sims, R. C., Sorensen, D. L. and Hulbert, M. (1987). Schmutzdecke Characterisation of Clinoptile-Ammended Slow Sand Filtration. *Journal of American Water Works Association,* **19**(12), 74-81.

Montgomery, J. M. (1985). *Water Treatment Principals and Design*. John Wiley & Sons, New York.

Montiel, A., Welte, B. and Barbier, J.M. (1988). Improvement of Slow Sand Filtration-Application to the Ivry Rehabilitation Project, Chapter 1, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Limited, Chichester; John Wiley & Sons, New York, 47-89.

Muhammad, N., Ellis, K., Parr, J. and Smith, M. D. (1996). Optimization of Slow Sand Filtration. *22nd WEDC Conference,* New Delhi, India.

Palmater, G., Manz, D., Jurkovic, A., McInnis, R., Unger, S., Kwan, K. K. and Dutka, B. J. (1999). Toxicant and Parasite Challenge of Manz Intermittent Slow Sand Filter. *Environmental Toxicology*, **14**(2), 217-225.

Paramasivam, R., Mhaisalkar, V. A. and Berthouex, P. M. (1981). Slow Sand Filter Design and Construction in Developing Countries. *Journal of American Water Works Association,* **75**(4), 178.

Phillips, S., Bowles, B., Bennison, G. and Drew, W. (1985). Slow Sand Filtration-Biological and Physical Considerations in Plant Design and Operation. Paper presented at the *Annual Convention of the Australian Water and Wastewater Association,* Melbourne.

Poynter, S. F. B. and Salde, J. S. (1977). The Removal of Viruses by Slow Sand Filtration. Progress in Water Technology. *Journal of International Association of Water Pollution Research,* **9**(1), 75-88.

Purdy, A. T. (1979). Structural Mechanics of Needlefelt Filter Media. *Proceedings of 2nd World Filtration Congress,* London.

Pyper, G. R. (1985). *Slow Sand Filter and Package Treatment Plant Evaluation: Operating Costs and Removal of Bacteria, Giardia, and Trihalomethanes.* EPA/600/S2-85/052, Water Engineering Research Laboratory, Cincinnati, Ohio.

Pyper, G. R. and Logsdon, G. S. (1991). Slow Sand Filter Design, Chapter 5, in: *Slow Sand Filtration,* Logsdon; G. S. (ed.). American Society of Civil Engineers, New York, 122-148.

Rachwal, A. J., Bauer, M. J., Chipps, M. J., Colbourne, J. S. and Foster, D. M. (1996). Comparison Between Slow Sand and High Rate Biofiltration, Part I, in: *Advances in Slow Sand and Alternative Biological Filtration*; Graham, N. J .D. and Collins, M. R. (eds.). John Wiley & Sons, Chichester,U. K., 3-10.

Rachwal, A., Rodman, D., West, J., and Zabel, T. (1984). Uprating and Upgrading of Slow Sand Filters by Pre-Ozonation. Paper presented at a *Seminar on Ozone in the U.K. Water Treatment Practice,* The Institute of Water Engineers and Scientists and The Water Research Centre, September 5, London, England.

Richards, A. D. (1974). The Distribution and Activity of Protozoa in Slow Sand Filters. *Journal of Protozoology,* **21**(3), 451-452.

Ridley, J. E. (1967). Experience in the Use of Slow Sand Filtration, Double Sand Filtration and Microstraining. *Proceedings of the Scociety for Water Treatment and Examination,* **16**, 170-191.

Riesenberg, F., Walters, B. B., Steele, A. and Ryder, R. A. (1995). Slow Sand Filters for a Small Water System. *Journal of American Water Works Association,* November, 48-56.

Sandstedt, H. N. (1979). Non-Wovens in Filtration applications. *Proceedings of 2nd World Filtration Conference,* London, 269-274.

Schellart, J. A. (1988). Benefits of Covered Slow Sand Filtration, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Ltd, Chichester; John Wiley & Sons, New York, 253-264.

Schuler, P. F., Ghosh, M. M. and Gopalan, P. (1991). Slow Sand and Diatomaceous Earth Filtration of Cysts and other Particulates. *Water Research,* **25**(8), 995–1005.

Seelaus, T. J., Hendricks, D. W. and Janonis, B. A. (1986). Design and Operation of a Slow Sand Filter. *Journal of American Water Works Association,* **78**(12), 35-41.

Slezak, A. L. and Sims, R. C. (1984). The Application and Effectiveness of Slow Sand Filtration in the United States. *Journal of American Water Works Association,* **76**(12) 38-43.

Smet, J. E. M. and Visscher, J. T. (1989). *Pre-treatment Methods for Community Water Supply.* International Reference Centre for Community Water Supply and Sanitation, The Hague, The Netherlands.

Spielman, L. A. and Goren, S. L. (1968). Model of Predicting Pressure Drop and Filtration Efficiency in Fibrous Media. *Environmental Science and Technology,* **2**(4), 279-287.

Tanner, S. A. and Ongerth, J. E. (1990). Evaluation of Slow Sand Filters in Northern Idaho. *Journal of American Water Works Association,* **82**(12), 51-61.

Timms, S. Salde, J. S., Fricker, C. R. (1995). Removal of *Cryptosporidium* by Slow Sand Filtration. *Water Science and Technology,* **31**(5/6), 81-84.

Toms, I. P. and Bayley, R. G. (1988). Slow Sand Filtration: an Approach to Practical Issues, Chapter 1, in: *Slow Sand Filtration: Recent Developments in Water Treatment Technology*; Graham, N. J. D. (ed.). Ellis Horwood Limited, Chichester; John Wiley & Sons, New York, 11-28.

Van Dijk, J. C. and Oomen, J. H. C. M. (1978). *Slow Sand Filtration for Community Water Supply in Developing Countries, Design and Construction Manual.* IRC Technical Paper No. 11, The Hague, The Netherlands.

Visscher, J. T. (1990). Slow Sand Filtration: Design, operation and Maintenance. *Journal of American Water Works Association,* **82**(6), 67-71.

Visscher, J. T. and Veenstra, S. (1985). *Slow Sand Filtration: Manual for Caretakers.* IRC Training Series No. 1, The Hague, The Netherlands.

Visscher, J. T., Paramasivam, R., Raman, A. and Heijnen, H. A. (1987). *Slow Sand Filtration for Community Water Supply: Planning, Design, Construction, Operation and Maintenance.* IRC Technical Paper No. 24, The Hague, The Netherlands.

Weber-Shirk, M. L. and Dick, R. I. (1999). Bacterivory by a Chrysophyte in Slow Sand Filters. *Water Research,* **33**(3), 631-638.

Weber-Shirk, M. L. and Dick, R. I. (1997a). Physical-Chemical Mechanisms in Slow Sand Filters. *Journal of American Water Works Association,* **89**(1), 87–100.

Weber-Shirk, M. L. and Dick, R. I. (1997b). Biological Mechanisms in Slow Sand Filters. *Journal of American Water Works Association,* **89**(2), 72–83.

Wegelin, M. (1984). *Horizontal Flow Roughing Filtration: An Appropriate Pretreatment for Slow Sand Filters in Developing Countries.* IRCWD Newsletter No.20, Zurich, Switzerland.

Wegelin, M. (1986). *Horizontal-Flow Roughing Filtration (HRF), A Design, Construction and Operational Manual.* IRCWD Repot No. 06/86, Switzerland.

WHO (1985). *Guidelines for Drinking Water Quality. Vol. 1, Drinking Water Quality Control in Small Community Supplies.* World Health Organization, Geneva, Switzerland.

Yao, K. M., Habibian, M. T. and O'Melia, C. R. (1971). Water and Waste Filtration: Concepts and Applications. *Environmental Science and Technology,* **11**(5), 1105-1112.

**APPENDICES**

## APPENDIX A: Sand Media Characteristics and Particle Size Distribution

### *A.1: Filter Sand Properties*

**Table A.1:** Filter Sand Physical and Chemical Properties*

| Physical Properties | Chemical Compositions |
|---|---|
| Mineral- Quartz | $SiO_2$ (Silicon Dioxide) – 99.48% |
| pH –Neutral (6.9/7.0) | $Fe_2O_3$ (Iron Oxide) - 0.06% |
| Colour- Tan/White | $Al_2O_3$ (Aluminum Oxide) – |
| Roundness- 0.6+ | $TiO_2$ (Titanium Dioxide) <0.01% |
| Sphericity- 0.6+ | CaO (Calcium Oxide) <0.01% |
| Hardness- 7.0 | MgO (Magnesium Oxide) |
| Specific gravity- 2.65 | |
| Unit Weight – 1650 kg/m$^3$ | |

* Provided by the Manufacturer (Northern Gravel Company, Iowa, U. S. A.)

According to the manufacturer, the filter sand was natural and mainly composed of silica. It was inert and odourless, did not have flat elongated grains, and met all AWWA recommendations for filter sand (AWWA B 100-96).

### *A.2: Filter Sand Particle Size Distribution*

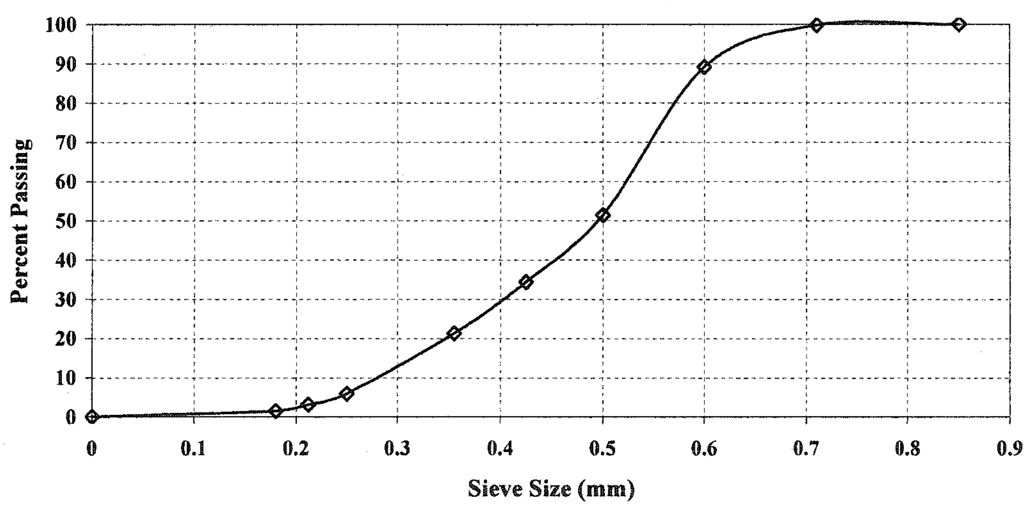



**Figure A.1:** Particle Size Distribution of Filter Sand

Effective size, ($d_{10}$) = 0.28 mm,

Uniformity coefficient, ($d_{60}/d_{10}$) = 1.88

# APPENDIX B: NWF Specifications

## *B.1 NWF Specifications Calculation*

The important properties of NWF are the porosity, mean fibre diameter and specific fibre surface area. For a particular fabric, the porosity and specific fibre surface area were calculated from the fabric bulk density, mean fibre diameter and fibre density by using the following relationships (B.1, B.2 and B.3 by Mbwette and Graham 1987; B.4 by Happel 1959):

$$\varepsilon_0 = 1 - (\frac{\rho_b}{\rho_f}) \qquad \text{(B.1)}$$

$$\rho_b = \frac{w}{z} \qquad \text{(B.2)}$$

$$\varepsilon_0 = 1 - \frac{d_f S_0}{4} \qquad \text{(B.3)}$$

$$K_h = d_f^2 \frac{\left[ -\ln\gamma - \frac{(1-\gamma^2)}{(1+\gamma^2)} \right]}{32\gamma} \qquad \text{(B.4)}$$

where,

$\rho_b$ = Fabric bulk density

$\rho_f$ = Fibre density (Polypropylyne fibre; specific gravity = 0.91)

z = Fabric thickness (One layer)

$d_f$ = Fibre diameter

w = Fabric mass per unit area

$\varepsilon_0$ = Clean bed porosity

$S_0$ = Specific surface area

$K_h$ = Permeability factor (=kν/G)

k = Hydraulic conductivity

ν = Kinematic viscosity (at $25^0$C, ν = 0.896 $mm^2/s$)

G = Gravitational acceleration (9810 $mm/s^2$), and

γ = Fibre volume fraction.

### *B.2 NWF Properties of Different Fabrics*

**Table B.1:** NWF Properties of Fabrics from Different Manufacturers

| Brand Name | Model | AOS* (mm) | z (mm) | w ($kg/m^2$) | $\rho_b$ ($kg/m^3$) | $\varepsilon_o$ | $\gamma = 1-\varepsilon_o$ | k (mm/s) | $K_h$ | $d_f$ (mm) | So ($m^2/m^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Mirafi | S600 | 0.212 | 1.65 | 0.2 | 123 | 0.86 | 0.14 | 2.5 | 0.00026 | 0.033 | 16519 |
| | S800 | 0.150 | 2.29 | 0.27 | 118 | 0.87 | 0.13 | 3.1 | 0.00032 | 0.035 | 14801 |
| | S1000 | 0.150 | 3.20 | 0.34 | 106 | 0.88 | 0.12 | 3.2 | 0.00033 | 0.032 | 14437 |
| | S1200 | 0.150 | 3.30 | 0.41 | 123 | 0.86 | 0.14 | 3.0 | 0.00031 | 0.036 | 15081 |
| | S1400 | 0.150 | 3.68 | 0.48 | 129 | 0.86 | 0.14 | 2.9 | 0.00030 | 0.037 | 15369 |
| | S1600 | 0.150 | 4.45 | 0.54 | 122 | 0.87 | 0.13 | 3.1 | 0.00032 | 0.036 | 14828 |
| Fibertex | F-400M | 0.080 | 46.00 | 0.42 | 9 | 0.99 | 0.01 | 60.0 | 0.00617 | 0.023 | 1712 |
| | F-650M | 0.070 | 57.00 | 0.67 | 12 | 0.99 | 0.01 | 40.0 | 0.00411 | 0.023 | 2297 |
| | F-1200M | 0.060 | 50.00 | 1.16 | 23 | 0.97 | 0.03 | 15.0 | 0.00154 | 0.022 | 4704 |
| | G-100 | 0.110 | 0.60 | 0.1 | 167 | 0.82 | 0.18 | 160.0 | 0.01644 | 0.356 | 2061 |
| | F-200 | 0.070 | 0.70 | 0.13 | 179 | 0.80 | 0.20 | 70.0 | 0.00719 | 0.254 | 3096 |
| | F-2B | 0.093 | 1.20 | 0.14 | 117 | 0.87 | 0.13 | 100.0 | 0.01028 | 0.197 | 2603 |
| | F-30 | 0.085 | 1.20 | 0.17 | 138 | 0.85 | 0.15 | 100.0 | 0.01028 | 0.231 | 2621 |
| | F-300 | 0.090 | 1.30 | 0.18 | 138 | 0.85 | 0.15 | 120.0 | 0.01233 | 0.254 | 2393 |
| | F-32M | 0.100 | 2.50 | 0.19 | 76 | 0.92 | 0.08 | 140.0 | 0.01439 | 0.160 | 2084 |
| | F-320 | 0.085 | 1.50 | 0.2 | 133 | 0.85 | 0.15 | 100.0 | 0.01028 | 0.224 | 2620 |
| | F-330 | 0.080 | 1.70 | 0.25 | 147 | 0.84 | 0.16 | 80.0 | 0.00822 | 0.221 | 2930 |
| | F-400 | 0.075 | 1.80 | 0.28 | 153 | 0.83 | 0.17 | 80.0 | 0.00822 | 0.229 | 2928 |
| | F-4M | 0.080 | 3.20 | 0.32 | 100 | 0.89 | 0.11 | 80.0 | 0.00822 | 0.153 | 2870 |
| | F-410 | 0.070 | 2.00 | 0.32 | 160 | 0.82 | 0.18 | 70.0 | 0.00719 | 0.225 | 3124 |
| | F-500 | 0.065 | 2.20 | 0.37 | 168 | 0.82 | 0.18 | 60.0 | 0.00617 | 0.220 | 3363 |

* AOS = Apparent opening size; AOS, z, w, and k are provided by the manufacturers.

**Table B.1:** Continued

| Brand Name | Model | AOS (mm) | z (mm) | W (kg/m$^2$) | $\rho_b$ (kg/m$^3$) | $\varepsilon_o$ | $\gamma = 1-\varepsilon_o$ | k (mm/s) | $K_h$ | $d_f$ (mm) | So (m$^2$/m$^3$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | LP-3.5 | 0.212 | 1.00 | 0.15 | 145 | 0.84 | 0.16 | 2.5 | 0.00026 | 0.039 | 16579 |
| | LP-4 | 0.212 | 1.10 | 0.16 | 141 | 0.84 | 0.16 | 2.2 | 0.00023 | 0.035 | 17675 |
| | LP-4.5 | 0.212 | 1.20 | 0.17 | 143 | 0.84 | 0.16 | 2.2 | 0.00023 | 0.035 | 17675 |
| | LP-6 | 0.212 | 1.80 | 0.22 | 122 | 0.87 | 0.13 | 2.4 | 0.00025 | 0.032 | 16855 |
| **Layfield** | LP-7 | 0.212 | 2.10 | 0.27 | 129 | 0.86 | 0.14 | 3.4 | 0.00035 | 0.040 | 14193 |
| | LP-8 | 0.180 | 2.10 | 0.27 | 129 | 0.86 | 0.14 | 3.8 | 0.00039 | 0.042 | 13426 |
| | LP-10 | 0.150 | 2.50 | 0.34 | 134 | 0.85 | 0.15 | 3.0 | 0.00031 | 0.039 | 15127 |
| | LP-12 | 0.150 | 2.80 | 0.43 | 155 | 0.83 | 0.17 | 2.9 | 0.00030 | 0.044 | 15369 |
| | LP-16 | 0.150 | 4.20 | 0.57 | 135 | 0.85 | 0.15 | 2.7 | 0.00028 | 0.037 | 15948 |
| | NO3 | 0.212 | 0.91 | 0.15 | 169 | 0.81 | 0.19 | 2.0 | 0.00021 | 0.040 | 18411 |
| | NO4 | 0.212 | 0.95 | 0.17 | 181 | 0.80 | 0.20 | 2.0 | 0.00021 | 0.044 | 18287 |
| | SD | 0.212 | 1.00 | 0.17 | 172 | 0.81 | 0.19 | 2.0 | 0.00021 | 0.041 | 18384 |
| | NO4.5 | 0.212 | 1.11 | 0.2 | 183 | 0.80 | 0.20 | 2.0 | 0.00021 | 0.044 | 18257 |
| | SO4 | 0.212 | 0.50 | 0.16 | 313 | 0.66 | 0.34 | 0.4 | 0.00004 | 0.040 | 34173 |
| **TerraTex** | NO5 | 0.212 | 1.18 | 0.22 | 184 | 0.80 | 0.20 | 2.0 | 0.00021 | 0.044 | 18249 |
| | NO6 | 0.212 | 1.33 | 0.26 | 196 | 0.78 | 0.22 | 2.0 | 0.00021 | 0.048 | 18086 |
| | NO7 | 0.212 | 1.33 | 0.3 | 224 | 0.75 | 0.25 | 2.0 | 0.00021 | 0.056 | 17574 |
| | NO8 | 0.150 | 1.33 | 0.33 | 245 | 0.73 | 0.27 | 2.0 | 0.00021 | 0.063 | 17125 |
| | N10 | 0.150 | 1.67 | 0.43 | 260 | 0.71 | 0.29 | 2.0 | 0.00021 | 0.068 | 16761 |
| | N12 | 0.150 | 2.22 | 0.49 | 220 | 0.76 | 0.24 | 2.0 | 0.00021 | 0.055 | 17666 |
| | N16 | 0.150 | 2.86 | 0.61 | 215 | 0.76 | 0.24 | 2.0 | 0.00021 | 0.053 | 17761 |
| | 4506 | 0.212 | 2.00 | 0.15 | 145 | 0.87 | 0.13 | 3.0 | 0.00031 | 0.036 | 15078 |
| | 4508 | 0.150 | 2.00 | 0.16 | 141 | 0.82 | 0.18 | 3.0 | 0.00031 | 0.047 | 15090 |
| **Propex** | 4510 | 0.150 | 1.67 | 0.17 | 143 | 0.72 | 0.28 | 2.0 | 0.00021 | 0.066 | 16930 |
| | 4512 | 0.150 | 2.22 | 0.22 | 122 | 0.76 | 0.24 | 2.0 | 0.00021 | 0.054 | 17681 |
| | 4516 | 0.150 | 2.85 | 0.27 | 129 | 0.76 | 0.24 | 2.0 | 0.00021 | 0.054 | 17698 |

## APPENDIX C: Bentonite Clay Suspension Concentration and Turbidity

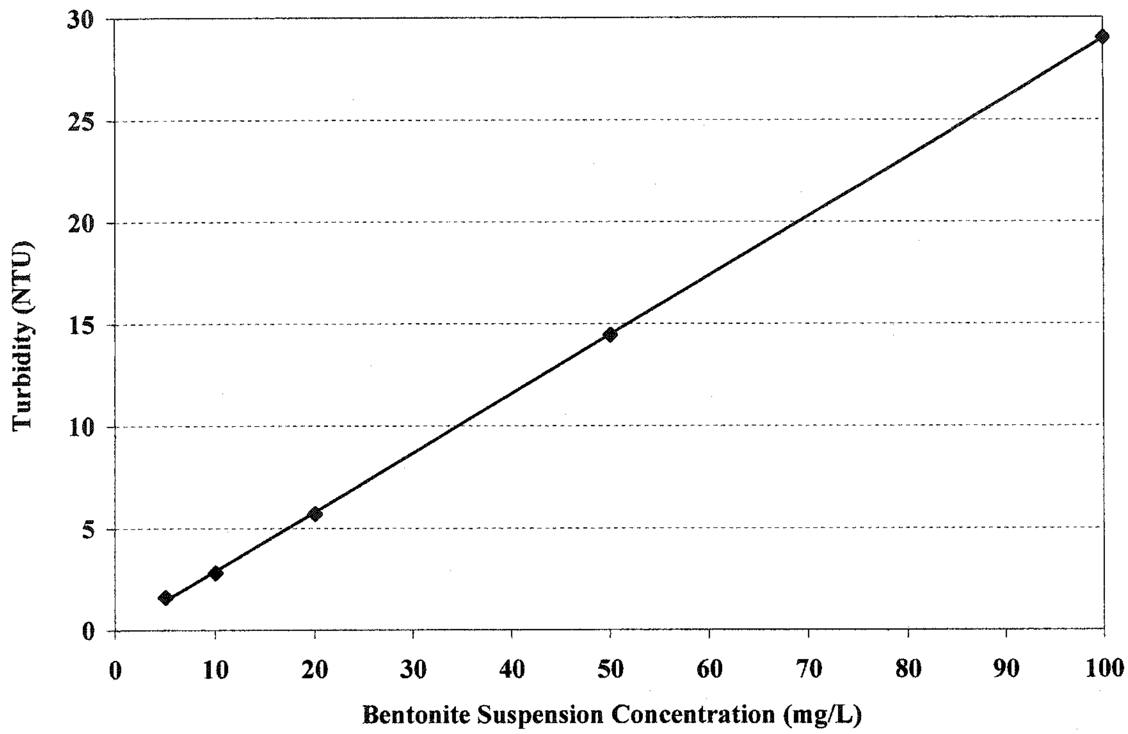



**Figure C.1:** Bentonite Clay Suspension Concentration vs Turbidity

Bentonite clay (B3378, CAS 1302-78-9) was bought from the Sigma Chemical Company, U. S. A.

***Particle sizes:***

Maximum Particle size = 74 µm

90 % passing size = 7 µm

10 % passing size = 2.7 µm.

## APPENDIX D: Algae Culturing

### *D.1: Sources of Algae Culture*

1. Local Pond – It was expected that different types of freshwater algae were present. Types were not determined but chlorophyll-A was measured to find the amount planktonic biomass after culturing.
2. Carolina Biological Supply
   a. *Euglena*: Unicellular Flagellate (Catalogue DN-15-1351)
   b. Green Algae Mixture (Catalogue DN-19-9980)
      Five representatives of green algae
      *Chlorella, Scenedesmus, Selenastrum, Ulothrix,* and *Volvox*

### *D.2: Growth Media*

1. Soil-Water Medium - Prepared in the laboratory.

2. Algal-Gro Freshwater Medium from Carolina Biological Supply Company (U. S. A.)- A universal media for freshwater algae, buffered at pH 7.8, rapidly gives dense cultures.

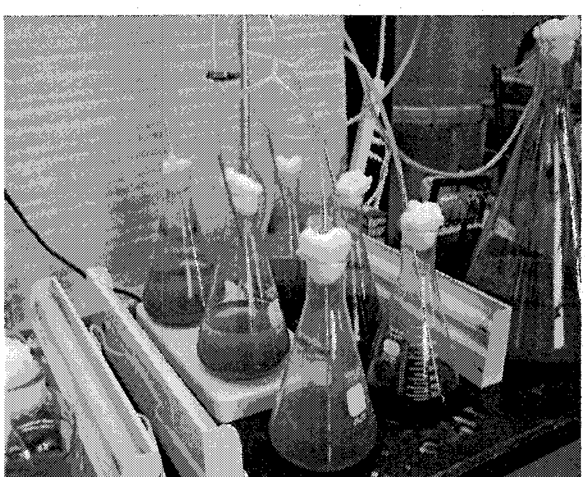
### *Soil-Water Medium Preparation*

a. Water: Tap water was used for preparing algal culture growth media. Tap water was boiled, cooled and aged for 7 days.
b. Nutrients: Liquid plant food ("Schultz-Instant" 10-15-10: phosphate, nitrate, potassium mixture) was used for the two main nutrients, phosphate and fixed nitrogen (in the form of nitrate, nitrite and ammonia).
c. Soil-Extract: Prepared in the laboratory. It provided trace minerals (iron, magnesium, cobalt etc.). In a 2 L, beaker 1 L deionised water, 100 g commercial potting soil, and 20 g garden soil were mixed, and boiled for about 15 minutes. After cooling for 30 minutes, the mixture was filtered by using several layers of paper towels and the filtrate was re-filtered by using a coffee filter. The filtrate was boiled for 10 minutes and stored for 2 days. After 2 days, it was again boiled for 10 minutes.

d. Media Preparation: 6 L of water, 6 full dropper (42 drops) of liquid plant food, and 100 ml of soil-extract were mixed to prepare 6.1 L batch of liquid algal culture growth medium.

***Algae Culturing***

100 mL of pond algae culture and 100 mL of soil-water medium were kept in a 250 mL Erlenmeyer flask. The mouth of the flask was covered with a cotton/gauze bung. A Pasteur pipette was use for gently bubbling the culture with air to maintain high levels of carbon dioxide and keep algae in suspension. Cool-white fluorescent bulbs, placed at 0.15 m distance, were used as the light source. Separate 20 mL of *Euglena* culture and 20 mL of green algae mixture culture were mixed with 150 mL of Algal-Gro Freshwater Medium in two different flasks and the light sources were provided. After 10 days, dense primary algae cultures were grown in all three flasks. Then, 20 mL of each of these three primary cultures were mixed in a 500 mL Erlenmeyer flask and 250 mL of soil-water media was added in that flask. Six of this type of flasks (Plate D.1 a) were prepared and kept in front of light sources with gentle air bubbling. In few days, dense cultures were observed in those flasks. Two 2 L of flasks (Plate D.1 b) were also prepared for culturing 1.5 L of culture in each. Required amount of the mix algae culture was used for the raw water preparation.



a. 500 mL of Erlenmeyer Flask

b. 2 L of Erlenmeyer Flask

**Plate D.1:** Culturing Algae

## APPENDIX E: Daily Raw Water Preparation and Characteristics

**Table E.1:** Raw Water Preparation (Run 1)

| Date | Day | Volume (L) | Aging (d) | AC Treat. | WW (L) | Algae (mL) | Bentonite (g) | Glucose (g) | Thiosulfate (g) |
|---|---|---|---|---|---|---|---|---|---|
| 6-Jan | **0** | 440 | 2 | No | 1 | 800 | 17.3 | | |
| 7-Jan | **1** | 440 | 1 | No | 1 | 900 | 17.6 | | |
| 8-Jan | **2** | 440 | 1 | No | 1 | 800 | 17.9 | | |
| 9-Jan | **3** | 440 | 1 | No | 1 | 800 | 17.5 | | |
| 10-Jan | **4** | 440 | 1 | No | 1 | 800 | 17.8 | | |
| 11-Jan | **5** | 440 | 1 | No | 1 | 700 | 17.9 | | |
| 12-Jan | **6** | 440 | 1 | No | 1 | 700 | 17.8 | | |
| 13-Jan | **7** | 440 | 1 | No | 2 | 700 | 17.6 | | |
| 14-Jan | **8** | | | | | | | | |
| 15-Jan | **9** | 440 | 2 | No | 2 | 800 | 17.8 | | |
| 16-Jan | **10** | 440 | 1 | No | 2 | 700 | 17.8 | | |
| 17-Jan | **11** | 440 | 1 | No | 2 | 700 | 17.9 | | |
| 18-Jan | **12** | 440 | 1 | No | 2 | 700 | 17.3 | | |
| 19-Jan | **13** | 440 | 1 | No | 2 | 700 | 17.4 | | |
| 20-Jan | **14** | 440 | 1 | No | 2 | 800 | 17.6 | | |
| 21-Jan | **15** | 440 | 2 | No | 2 | 800 | 18 | | |
| 22-Jan | **16** | 440 | 1 | No | 2 | 700 | 17.9 | | |
| 23-Jan | **17** | | | | | | | | |
| 24-Jan | **18** | 440 | 2 | No | 2 | 800 | 17.2 | | |
| 25-Jan | **19** | 440 | 1 | No | 2 | 700 | 17.3 | | |
| 26-Jan | **20** | | | | | | | | |

**Table E.2:** Raw Water Preparation (Run 3)

| Date | Day | Volume (L) | Aging (d) | AC Treat. | WW (L) | Algae (mL) | Bentonite (g) | Glucose (g) | Thiosulfate (g) |
|---|---|---|---|---|---|---|---|---|---|
| 6-May | **0** | 440 | 2 | Y | 1 | 250 | | 5.3 | |
| 7-May | **1** | 440 | 1 | Y | 2 | 300 | | 5.2 | |
| 8-May | **2** | 440 | 1 | Y | 2 | 350 | | 7.9 | |
| 9-May | **3** | 440 | 1 | Y | 2 | 300 | | 8.1 | |
| 10-May | **4** | 440 | 1 | Y | 2 | 350 | | 7.9 | |
| 11-May | **5** | 440 | 1 | Y | 2 | 250 | | 7.8 | |
| 12-May | **6** | 440 | 1 | Y | 1 | 300 | | 7.8 | |
| 13-May | **7** | 440 | 1 | Y | 1 | 250 | | 8.2 | |
| 14-May | **8** | 440 | 1 | Y | 1 | 300 | | 7.9 | |
| 15-May | **9** | 440 | 1 | Y | 1 | 250 | | 7.9 | |
| 16-May | **10** | | | | | | | | |

AC Treat. = Activated Carbon Treated
WW = Treated Wastewater Primary Effluent
Algae = Dense Algae Culture
Bentonite = Bentonite Clay
Thiosulfate = Sodium Thiosulfate
Y = Yes

**Table E.3:** Raw Water Preparation (Run 2)

| Date | Day | Volume (L) | Aging (d) | AC Treat. | WW (L) | Algae (mL) | Bentonite (g) | Glucose (g) | Thiosulfate (g) |
|---|---|---|---|---|---|---|---|---|---|
| 4-Mar | **0** | 440 | 2 | No | 6 | 500 | | | |
| 5-Mar | **1** | 440 | 1 | No | 5 | 500 | | | |
| 6-Mar | **2** | 440 | 1 | No | 4 | 500 | | | |
| 7-Mar | **3** | | | | | | | | |
| 8-Mar | **4** | 440 | 2 | No | 6 | 500 | | | |
| 9-Mar | **5** | | | | | | | | |
| 10-Mar | **6** | 440 | 2 | No | 6 | 700 | | | |
| 11-Mar | **7** | 440 | 1 | No | 6 | 700 | | | |
| 12-Mar | **8** | 440 | 1 | No | 5 | 600 | | | |
| 13-Mar | **9** | | | | | | | | |
| 14-Mar | **10** | 440 | 2 | No | 5 | 500 | | | |
| 15-Mar | **11** | 440 | 1 | No | 5 | 500 | | | |
| 16-Mar | **12** | | | | | | | | |
| 17-Mar | **13** | 440 | 2 | No | 4 | 500 | | | |
| 18-Mar | **14** | 440 | 1 | No | 4 | 500 | | | |
| 19-Mar | **15** | 440 | 1 | No | 3 | 500 | | | |
| 20-Mar | **16** | | | | | | | | |
| 21-Mar | **17** | 440 | 2 | No | 2 | 300 | | | |
| 22-Mar | **18** | 440 | 1 | No | 3 | 400 | | | |
| 23-Mar | **19** | | | | | | | | |
| 24-Mar | **20** | 440 | 2 | No | 3 | 500 | | | 2.5 |
| 25-Mar | **21** | 440 | 1 | No | 3 | 500 | | | 3.2 |
| 26-Mar | **22** | 440 | 1 | No | 3 | 500 | | 9 | 3.5 |
| 27-Mar | **23** | 440 | 1 | No | 4 | 400 | | 8.8 | 3.5 |
| 28-Mar | **24** | | | | | | | 4.1 | |
| 29-Mar | **25** | 440 | 2 | No | 4 | 400 | | 9 | 4.1 |
| 30-Mar | **26** | | | | | | | 3.8 | |
| 31-Mar | **27** | 250 | 2 | No | 2.5 | 200 | | 4.5 | 3.2 |
| 1-Apr | **28** | 250 | 1 | No | 2 | 250 | | 4.6 | 3.3 |
| 2-Apr | **29** | 250 | 1 | No | 2 | 300 | | 4.5 | |
| 3-Apr | **30** | 250 | 1 | No | 3 | 250 | | 4.8 | |
| 4-Apr | **31** | 250 | 1 | No | 2 | 250 | | 5 | |
| 5-Apr | **32** | 250 | 1 | No | 2 | 300 | | 5 | |
| 6-Apr | **33** | 250 | 1 | No | 2 | 400 | | 4.9 | |
| 7-Apr | **34** | 250 | 1 | No | 2 | 300 | | 4.5 | |
| 8-Apr | **35** | 250 | 1 | No | 2 | 400 | | 4.5 | |
| 9-Apr | **36** | 250 | 1 | Y | 2 | 250 | | 4.5 | |
| 10-Apr | **37** | 300 | 1 | Y | 2 | 400 | | 4.5 | |
| 11-Apr | **38** | 400 | 1 | Y | 2 | 500 | | 6 | |
| 12-Apr | **39** | 440 | 1 | Y | 2 | 500 | | 8.5 | |
| 13-Apr | **40** | 440 | 1 | Y | 2 | 400 | | 9 | |
| 14-Apr | **41** | 440 | 1 | Y | 2 | 450 | | 8.9 | |
| 15-Apr | **42** | 440 | 1 | Y | 3 | 500 | | 9.1 | |
| 16-Apr | **43** | | | | | | | 4 | |
| 17-Apr | **44** | 440 | 2 | Y | 2 | 300 | | 9 | |
| 18-Apr | **45** | 440 | 1 | Y | 2 | 400 | | 9 | |
| 19-Apr | **46** | 400 | 1 | Y | 2 | 300 | | 8.5 | |
| 20-Apr | **47** | 400 | 1 | Y | 1.5 | 250 | | 8 | |
| 21-Apr | **48** | | | | | | | 4.5 | |
| 22-Apr | **49** | 440 | 2 | Y | 4 | 750 | | 10 | |
| 23-Apr | **50** | | | | | | | 4 | |
| 24-Apr | **51** | 440 | 2 | Y | 3 | 500 | | 9.6 | |
| 25-Apr | **52** | 440 | 1 | Y | 2 | 450 | | 9 | |
| 26-Apr | **53** | 440 | 1 | Y | 2 | 500 | | 9 | |
| 27-Apr | **54** | 440 | 1 | Y | 2 | 400 | | 8.8 | |
| 28-Apr | **55** | 400 | 1 | Y | 2 | 500 | | 9 | |
| 29-Apr | **56** | 440 | 1 | Y | 2 | 500 | | 9 | |
| 30-Apr | **57** | 440 | 1 | Y | 1.5 | 350 | | 8.5 | |
| 1-May | **58** | 400 | 1 | Y | 2 | 500 | | 9 | |
| 2-May | **59** | 400 | 1 | Y | 1.5 | 300 | | 8 | |
| 3-May | **60** | 440 | 1 | Y | 2 | 400 | | 8 | |
| 4-May | **61** | | | | | | | | |

**Table E.4:** Raw Water Characteristics (Run 1)

| Date | Day | Temp (°C) | DO (mg/L) | pH | Turb. (NTU) | TOC (mg/L) | Nitrate (mg/L) | Ammonia (mg/L) | TC (CFU/100mL) | *E.coli* (CFU/100mL) | Chlorophyll-A (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6-Jan | 0 | 19.7 | 8.64 | 6.83 | 11 | 0.51 | | | | | 2.3 |
| 7-Jan | 1 | 19.2 | 7.89 | 6.88 | 9.9 | 0.47 | | | | | 3.1 |
| 8-Jan | 2 | 18.4 | 8.24 | 7.46 | 11 | 0.49 | | | | | |
| 9-Jan | 3 | 18.9 | 8.68 | 7.86 | 9.5 | 0.35 | | | | | 1.5 |
| 10-Jan | 4 | 19.6 | 8.48 | 7.57 | 11 | 0.44 | | | | | 3.4 |
| 11-Jan | 5 | 19.8 | 7.95 | 7.84 | 11 | 0.37 | | | | | |
| 12-Jan | 6 | 18.7 | 8.31 | 7.49 | 10 | 0.46 | | | | | |
| 13-Jan | 7 | 21.2 | 9.34 | 7.47 | 10 | 0.67 | | | | | 1.8 |
| 14-Jan | 8 | 20.8 | 8.67 | 7.42 | 9.5 | 0.26 | | | | | |
| 15-Jan | 9 | 21.2 | 8.98 | 7.56 | 12 | 0.45 | | | | | 2.3 |
| 16-Jan | 10 | 19.5 | 9.45 | 7.65 | 10 | 0.54 | | | | | 3.4 |
| 17-Jan | 11 | 19.8 | 8.89 | 7.41 | 9.7 | 0.41 | | | | | |
| 18-Jan | 12 | 20.6 | 8.82 | 7.59 | 11 | 0.24 | | | | | |
| 19-Jan | 13 | 21.4 | 9.56 | 6.97 | 11 | 0.28 | | | | | 4.1 |
| 20-Jan | 14 | 22.3 | 8.74 | 7.58 | 12 | 0.31 | | | | | 3.2 |
| 21-Jan | 15 | 21.7 | 8.63 | 7.48 | 12 | 0.27 | | | | | |
| 22-Jan | 16 | 21.5 | 8.98 | 7.56 | 12 | 0.22 | | | | | 2.9 |
| 23-Jan | 17 | 21.7 | 9.56 | 7.48 | 10 | 0.26 | | | | | |
| 24-Jan | 18 | 21.4 | 9.02 | 7.55 | 9.6 | 0.23 | | | | | 4.2 |
| 25-Jan | 19 | 20.6 | 9.2 | 6.93 | 11 | 0.28 | | | | | 3.5 |
| 26-Jan | 20 | 21.6 | 8.02 | 7.48 | 9.2 | 0.36 | | | | | |

**Table E.5:** Raw Water Characteristics (Run 3)

| Date | Day | Temp (°C) | DO (mg/L) | pH | Turb. (NTU) | TOC (mg/L) | Nitrate (mg/L) | Ammonia (mg/L) | TC (CFU/100mL) | *E.coli* (CFU/100mL) | Chlorophyll-A (µg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6-May | 0 | 22.3 | 8.9 | 7.33 | 1.8 | 4.68 | 1.14 | 0.17 | | | |
| 7-May | 1 | 21.8 | 8.78 | 7.63 | 1.6 | 4.82 | 0.37 | 0.39 | 7570 | 1080 | 3.9 |
| 8-May | 2 | 21.7 | 9.43 | 6.87 | 1.9 | 6.89 | 0.67 | 0.28 | 6420 | 820 | |
| 9-May | 3 | 21.8 | 9.98 | 6.78 | 1.7 | 7.31 | 0.45 | 0.39 | | | 4.1 |
| 10-May | 4 | 21.1 | 9.84 | 6.89 | 1.6 | 7.21 | 0.84 | 0.16 | 3380 | 190 | |
| 11-May | 5 | 21.3 | 9.85 | 6.75 | 1.8 | 7.54 | 0.65 | 0.35 | 5870 | 370 | 3.7 |
| 12-May | 6 | 21.9 | 9.21 | 6.82 | 1.4 | 7.59 | 0.51 | 0.22 | | | |
| 13-May | 7 | 21.2 | 9.43 | 7.29 | 1.7 | 8.12 | 0.38 | 0.13 | 10320 | 990 | 3.1 |
| 14-May | 8 | 21.8 | 9.69 | 6.75 | 2 | 7.06 | 0.64 | 0.46 | | | 2.4 |
| 15-May | 9 | 22.1 | 9.46 | 7.41 | 1.6 | 6.88 | 0.43 | 0.31 | | | 2.6 |
| 16-May | 10 | 22.4 | 8.97 | 7.14 | 1.5 | 4.31 | 1.16 | 0.15 | | | |

| | | | | | |
|---|---|---|---|---|---|
| Temp. | = | Temperature | TC | = | Total Coliform |
| DO | = | Dissolved Oxygen | FC | = | Fecal Coliform |
| Turb. | = | Turbidity | Nitrate | = | $NO_3^-$-Nitrogen (mg/L) |
| TOC | = | Total Organic Carbon | Ammonia | = | $NH_3$-Nitrogen (mg/L) |

## Table E.6: Raw Water Characteristics (Run 2)

| Date | Day | Temp ($^0$C) | DO (mg/L) | pH | Turb. (NTU) | TOC (mg/L) | Nitrate (mg/L) | Ammonia (mg/L) | TC (CFU/100mL) | *E.coli* (CFU/100mL) | Chlorophyll-A (μg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4-Mar | **0** | 23.2 | 7.36 | 7.48 | 1.4 | 0.58 | 0.95 | 0.75 | <1 | <1 | 5.3 |
| 5-Mar | **1** | 23.2 | 7.58 | 7.45 | 1.4 | 0.63 | 1.22 | 0.66 | <1 | <1 | 4.9 |
| 6-Mar | **2** | 23.1 | 7.53 | 7.21 | 1.6 | 0.56 | 1.4 | 0.64 | | | |
| 7-Mar | **3** | 22.8 | 6.95 | 7.12 | 1.6 | 0.27 | | | <1 | <1 | |
| 8-Mar | **4** | 22.9 | 8.88 | 7.35 | 1.8 | 0.57 | 1.54 | 0.9 | | | 3.5 |
| 9-Mar | **5** | 22.6 | 7.21 | 7.36 | 1.5 | 0.36 | 2.1 | 0.77 | | | |
| 10-Mar | **6** | 23.4 | 8.9 | 7.59 | 1.6 | 0.47 | | | | | |
| 11-Mar | **7** | 23.1 | 8.1 | 6.89 | 1.8 | 0.45 | | | | | 5.8 |
| 12-Mar | **8** | 23 | 7.45 | 7.12 | 1.9 | 0.51 | 1.65 | 0.61 | | | |
| 13-Mar | **9** | 22.5 | 8.64 | 7.25 | 2 | 0.41 | 1.85 | 0.58 | | | |
| 14-Mar | **10** | 22.7 | 8.1 | 6.72 | 1.5 | 0.46 | | | | | 4.1 |
| 15-Mar | **11** | 21.9 | 8.6 | 7.49 | 1.6 | 0.42 | | | | | 4.3 |
| 16-Mar | **12** | 22.2 | 7.25 | 7.34 | 1.4 | 0.34 | 1.98 | 0.67 | <1 | <1 | |
| 17-Mar | **13** | 23.1 | 7.48 | 6.43 | 1.8 | 0.38 | 1.21 | 0.88 | | | |
| 18-Mar | **14** | 23.2 | 8.8 | 7.15 | 1.9 | 0.41 | 1.52 | 0.75 | | | 5.1 |
| 19-Mar | **15** | 22.6 | 7.68 | 6.86 | 1.6 | 0.36 | | | | | |
| 20-Mar | **16** | 22.7 | 7.3 | 6.9 | 1.7 | 0.24 | | | | | |
| 21-Mar | **17** | 21.7 | 9.1 | 7.45 | 1.5 | 0.27 | | | | | |
| 22-Mar | **18** | 22.2 | 8.78 | 7.16 | 1.5 | 0.25 | 1.75 | 0.85 | | | 5.6 |
| 23-Mar | **19** | 22.4 | 7.46 | 7.21 | 1.6 | 0.22 | 1.73 | 0.62 | | | |
| 24-Mar | **20** | 22.7 | 9.6 | 7.68 | 1.4 | 0.42 | | | | | |
| 25-Mar | **21** | 22.1 | 8.8 | 6.76 | 1.8 | 0.46 | | | | | 3.9 |
| 26-Mar | **22** | 20.9 | 8.1 | 6.89 | 1.8 | 9.03 | 1.65 | 0.68 | <1 | <1 | 4.2 |
| 27-Mar | **23** | 21.6 | 9.76 | 7.35 | 2 | 8.53 | 1.45 | 0.51 | <1 | <1 | |
| 28-Mar | **24** | 21.4 | 7.46 | 7.48 | 1.9 | 8.12 | | | | | |
| 29-Mar | **25** | 23.2 | 7.81 | 6.49 | 1.7 | 8.12 | 1.08 | 0.47 | | | 3.4 |
| 30-Mar | **26** | 22.4 | 7.11 | 7.46 | 1.6 | 6.75 | 1.85 | 0.38 | | | |
| 31-Mar | **27** | 23.3 | 9.74 | 7.23 | 1.6 | 4.88 | | | | | |
| 1-Apr | **28** | 22.1 | 8.46 | 6.83 | 1.7 | 4.73 | | | | | 4.9 |
| 2-Apr | **29** | 20.6 | 9.1 | 7.32 | 1.4 | 4.69 | | | <1 | <1 | 1.8 |
| 3-Apr | **30** | 21.4 | 8.25 | 7.26 | 1.9 | 4.53 | 1.24 | 0.65 | | | 1.2 |
| 4-Apr | **31** | 21.3 | 7.89 | 7.49 | 1.4 | 4.68 | 0.96 | 0.61 | | | |
| 5-Apr | **32** | 20.9 | 9.35 | 6.69 | 1.8 | 4.57 | 1.34 | 0.34 | | | |
| 6-Apr | **33** | 23.1 | 9.78 | 7.49 | 1.8 | 4.85 | | | | | 3.1 |
| 7-Apr | **34** | 22.1 | 8.1 | 6.98 | 1.7 | 4.75 | | | | | |
| 8-Apr | **35** | 20.1 | 7.86 | 7.13 | 1.9 | 4.62 | | | | | |
| 9-Apr | **36** | 21.9 | 8.67 | 7.74 | 2 | 5.21 | 1.36 | 0.34 | 3670 | 280 | |
| 10-Apr | **37** | 22.3 | 8.46 | 7.16 | 1.7 | 4.92 | 1.80 | 0.44 | 3750 | 160 | 5.1 |
| 11-Apr | **38** | 19.4 | 9.8 | 6.49 | 1.5 | 4.62 | 2.10 | 0.27 | 5430 | 470 | 4.7 |
| 12-Apr | **39** | 22.4 | 8.75 | 7.78 | 1.6 | 7.89 | | | 4880 | 380 | |
| 13-Apr | **40** | 21.1 | 7.89 | 6.78 | 1.9 | 7.78 | | | | | |
| 14-Apr | **41** | 20.3 | 7.64 | 7.54 | 1.4 | 7.51 | 1.60 | 0.45 | | | 2.1 |
| 15-Apr | **42** | 21.7 | 8.91 | 6.56 | 1.6 | 7.91 | 1.54 | 0.64 | 3880 | 170 | |
| 16-Apr | **43** | 22.1 | 7.49 | 6.65 | 1.8 | 8.1 | 2.10 | 0.91 | 3520 | 220 | |
| 17-Apr | **44** | 23.4 | 9.86 | 7.33 | 1.9 | 7.78 | | | | | |
| 18-Apr | **45** | 20.3 | 8.42 | 6.94 | 1.4 | 7.69 | | | | | 1.9 |
| 19-Apr | **46** | 21.4 | 9.1 | 7.37 | 1.6 | 7.12 | 1.40 | 0.76 | | | 2.6 |
| 20-Apr | **47** | 19.4 | 10.1 | 6.64 | 1.9 | 6.89 | 1.32 | 0.74 | 5890 | 420 | |
| 21-Apr | **48** | 19.1 | 8.45 | 6.74 | 1.8 | 7.86 | | | 4780 | 590 | |
| 22-Apr | **49** | 21.3 | 9.78 | 7.56 | 1.9 | 8.89 | 2.10 | 0.63 | 7250 | 620 | 5.2 |
| 23-Apr | **50** | 21.6 | 8.1 | 7.5 | 2 | 7.59 | 1.54 | 0.65 | 9430 | 780 | |
| 24-Apr | **51** | 22.4 | 9.76 | 6.89 | 2 | 8.12 | 1.50 | 0.45 | | | 4.5 |
| 25-Apr | **52** | 20.4 | 8.86 | 6.89 | 1.8 | 7.48 | | | 6860 | 490 | |
| 26-Apr | **53** | 20.5 | 9.88 | 6.84 | 1.7 | 7.62 | | | | | |
| 27-Apr | **54** | 19.9 | 9.45 | 7.49 | 1.6 | 7.69 | | | | | |
| 28-Apr | **55** | 22.5 | 9.34 | 7.4 | 1.8 | 7.42 | 1.12 | 0.22 | 6590 | 320 | 3.8 |
| 29-Apr | **56** | 21 | 10.2 | 7.23 | 1.5 | 7.35 | 1.54 | 0.63 | 10930 | 370 | |
| 30-Apr | **57** | 21.1 | 9.73 | 7.67 | 1.9 | 7.26 | 1.36 | 0.34 | | | |
| 1-May | **58** | 22.6 | 9.41 | 7.21 | 1.4 | 7.91 | | | | | 4.6 |
| 2-May | **59** | 21.4 | 7.46 | 7.22 | 1.7 | 7.68 | 1.25 | 0.33 | | | |
| 3-May | **60** | 22.3 | 8.81 | 7.45 | 1.6 | 7.78 | 1.60 | 0.35 | | | 3.2 |
| 4-May | **61** | 20.1 | 7.11 | 7.4 | 1.5 | 4.35 | | | | | |

## APPENDIX F: Coliform Growth Media Preparation for Membrane Technique

### *F.1 m-Endo Total Coliform Growth Media*

The media broth base (m-Endo Broth Base, MB000000E) was obtained from Millipore Corporation, U. S. A. Media was prepared by the following procedures:

- A sterile solution of deionized water containing 2% ethanol ($CH_3CH_2OH$, 95 %) was prepared.
- 4.8 g of dehydrated broth base was added in 100 mL prepared solution.
- The solution was mixed carefully and heated to the boiling point.
- The solution was cooled to the room temperature.
- When solids precipitated, the clarified medium was transferred in to a new sterile screw caped bottle and stored in a refrigerator at 4 $^{o}$C.

The prepared media was used for no more than two weeks. The sterile petri dishes were prepared by adding 2 mL of m-Endo broth over a sterile absorbent pad about 1 hour before the use.

### *F.2 m-FC Fecal Coliform Growth Media*

The media broth base (m-FC Broth Base, MB000000F) was supplied by Millipore Corporation, U. S. A. Media was prepared by the following procedures:

- 3.7 g of dehydrated broth base was added in 100 mL sterile deionized water.
- 1 mL rosolic acid was added.
- The pH was adjusted to 7.4 by 0.1 N HCl.
- The solution was mixed carefully and heated to the boiling point.
- The solution was cooled to the room temperature and transferred in to a sterile screw caped bottle and stored in a refrigerator at 4 $^{o}$C.

The rosolic acid solution was prepared by adding 1 g rosolic acid powder (CAT MB000000R, Millipore Corporation) in 100 mL sterile solution of 0.2 N NaOH. The prepared media was used for no more than two weeks. The sterile petri dishes were prepared by adding 2 mL of m-FC broth over a sterile absorbent pad about 1 hour before the use.

# APPENDIX G: IDEXX Quanti-Tray®/2000 MPN Table

| # Large Wells Positive | # Small Wells Positive 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | <1 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.0 | 9.0 | 10.0 | 11.0 | 12.0 | 13.0 | 14.0 | 15.1 | 16.1 | 17.1 | 18.1 | 19.1 | 20.2 | 21.2 | 22.2 | 23.2 | 24.3 |
| 1 | 1.0 | 2.0 | 3.0 | 4.0 | 5.0 | 6.0 | 7.0 | 8.1 | 9.1 | 10.1 | 11.1 | 12.1 | 13.2 | 14.2 | 15.2 | 16.2 | 17.3 | 18.3 | 19.3 | 20.4 | 21.4 | 22.4 | 23.5 | 24.5 | 25.6 |
| 2 | 2.0 | 3.0 | 4.1 | 5.1 | 6.1 | 7.1 | 8.1 | 9.2 | 10.2 | 11.2 | 12.2 | 13.3 | 14.3 | 15.3 | 16.4 | 17.4 | 18.5 | 19.5 | 20.6 | 21.6 | 22.6 | 23.7 | 24.8 | 25.8 | 26.9 |
| 3 | 3.1 | 4.1 | 5.1 | 6.1 | 7.2 | 8.2 | 9.2 | 10.3 | 11.3 | 12.4 | 13.4 | 14.4 | 15.5 | 16.5 | 17.6 | 18.6 | 19.7 | 20.8 | 21.8 | 22.9 | 23.9 | 25.0 | 26.1 | 27.1 | 28.2 |
| 4 | 4.1 | 5.2 | 6.2 | 7.2 | 8.3 | 9.3 | 10.4 | 11.4 | 12.5 | 13.5 | 14.6 | 15.6 | 16.7 | 17.8 | 18.8 | 19.9 | 21.0 | 22.0 | 23.1 | 24.2 | 25.2 | 26.3 | 27.4 | 28.5 | 29.6 |
| 5 | 5.2 | 6.3 | 7.3 | 8.4 | 9.4 | 10.5 | 11.5 | 12.6 | 13.7 | 14.7 | 15.8 | 16.9 | 17.9 | 19.0 | 20.1 | 21.2 | 22.2 | 23.3 | 24.4 | 25.5 | 26.6 | 27.7 | 28.8 | 29.9 | 31.0 |
| 6 | 6.3 | 7.4 | 8.4 | 9.5 | 10.6 | 11.6 | 12.7 | 13.8 | 14.9 | 15.9 | 17.0 | 18.1 | 19.2 | 20.3 | 21.4 | 22.5 | 23.6 | 24.7 | 25.8 | 26.9 | 28.0 | 29.1 | 30.2 | 31.3 | 32.4 |
| 7 | 7.4 | 8.5 | 9.6 | 10.7 | 11.8 | 12.8 | 13.9 | 15.0 | 16.1 | 17.2 | 18.3 | 19.4 | 20.5 | 21.6 | 22.7 | 23.8 | 24.9 | 26.0 | 27.1 | 28.3 | 29.4 | 30.5 | 31.6 | 32.8 | 33.9 |
| 8 | 8.6 | 9.7 | 10.8 | 11.9 | 13.0 | 14.1 | 15.2 | 16.3 | 17.4 | 18.5 | 19.6 | 20.7 | 21.8 | 22.9 | 24.1 | 25.2 | 26.3 | 27.4 | 28.6 | 29.7 | 30.8 | 32.0 | 33.1 | 34.3 | 35.4 |
| 9 | 9.8 | 10.9 | 12.0 | 13.1 | 14.2 | 15.3 | 16.4 | 17.5 | 18.7 | 19.8 | 20.9 | 22.0 | 23.2 | 24.3 | 25.4 | 26.6 | 27.7 | 28.9 | 30.0 | 31.2 | 32.3 | 33.5 | 34.6 | 35.8 | 37.0 |
| 10 | 11.0 | 12.1 | 13.2 | 14.3 | 15.5 | 16.6 | 17.7 | 18.9 | 20.0 | 21.1 | 22.3 | 23.4 | 24.6 | 25.7 | 26.9 | 28.0 | 29.2 | 30.3 | 31.5 | 32.7 | 33.8 | 35.0 | 36.2 | 37.4 | 38.6 |
| 11 | 12.2 | 13.4 | 14.5 | 15.6 | 16.8 | 17.9 | 19.1 | 20.2 | 21.4 | 22.5 | 23.7 | 24.8 | 26.0 | 27.2 | 28.3 | 29.5 | 30.7 | 31.9 | 33.0 | 34.2 | 35.4 | 36.6 | 37.8 | 39.0 | 40.2 |
| 12 | 13.5 | 14.6 | 15.8 | 16.9 | 18.1 | 19.3 | 20.4 | 21.6 | 22.7 | 23.9 | 25.1 | 26.3 | 27.5 | 28.6 | 29.8 | 31.0 | 32.2 | 33.4 | 34.6 | 35.8 | 37.0 | 38.2 | 39.4 | 40.7 | 41.9 |
| 13 | 14.8 | 16.0 | 17.1 | 18.3 | 19.5 | 20.6 | 21.8 | 23.0 | 24.2 | 25.4 | 26.6 | 27.8 | 29.0 | 30.2 | 31.4 | 32.6 | 33.8 | 35.0 | 36.2 | 37.5 | 38.7 | 39.9 | 41.1 | 42.4 | 43.6 |
| 14 | 16.1 | 17.3 | 18.5 | 19.7 | 20.9 | 22.1 | 23.3 | 24.4 | 25.7 | 26.9 | 28.1 | 29.3 | 30.5 | 31.7 | 33.0 | 34.2 | 35.4 | 36.7 | 37.9 | 39.1 | 40.4 | 41.6 | 42.9 | 44.2 | 45.4 |
| 15 | 17.5 | 18.7 | 19.9 | 21.1 | 22.3 | 23.5 | 24.7 | 25.9 | 27.2 | 28.4 | 29.6 | 30.9 | 32.1 | 33.3 | 34.6 | 35.8 | 37.1 | 38.4 | 39.6 | 40.9 | 42.2 | 43.4 | 44.7 | 46.0 | 47.3 |
| 16 | 18.9 | 20.1 | 21.3 | 22.6 | 23.8 | 25.0 | 26.2 | 27.5 | 28.7 | 30.0 | 31.2 | 32.5 | 33.7 | 35.0 | 36.3 | 37.5 | 38.8 | 40.1 | 41.4 | 42.7 | 44.0 | 45.3 | 46.6 | 47.9 | 49.2 |
| 17 | 20.3 | 21.6 | 22.8 | 24.0 | 25.3 | 26.5 | 27.8 | 29.1 | 30.3 | 31.6 | 32.9 | 34.1 | 35.4 | 36.7 | 38.0 | 39.3 | 40.6 | 41.9 | 43.2 | 44.5 | 45.9 | 47.2 | 48.5 | 49.8 | 51.2 |
| 18 | 21.8 | 23.1 | 24.3 | 25.6 | 26.9 | 28.1 | 29.4 | 30.7 | 32.0 | 33.3 | 34.6 | 35.9 | 37.2 | 38.5 | 39.8 | 41.1 | 42.4 | 43.8 | 45.1 | 46.4 | 47.8 | 49.1 | 50.5 | 51.9 | 53.2 |
| 19 | 23.3 | 24.6 | 25.9 | 27.2 | 28.5 | 29.8 | 31.1 | 32.4 | 33.7 | 35.0 | 36.3 | 37.6 | 39.0 | 40.3 | 41.6 | 43.0 | 44.3 | 45.7 | 47.1 | 48.4 | 49.8 | 51.2 | 52.6 | 54.0 | 55.4 |
| 20 | 24.9 | 26.2 | 27.5 | 28.8 | 30.1 | 31.4 | 32.8 | 34.1 | 35.4 | 36.8 | 38.1 | 39.5 | 40.8 | 42.2 | 43.6 | 44.9 | 46.3 | 47.7 | 49.1 | 50.5 | 51.9 | 53.3 | 54.7 | 56.1 | 57.6 |
| 21 | 26.5 | 27.8 | 29.2 | 30.5 | 31.8 | 33.2 | 34.5 | 35.9 | 37.3 | 38.6 | 40.0 | 41.4 | 42.8 | 44.1 | 45.5 | 46.9 | 48.4 | 49.8 | 51.2 | 52.6 | 54.1 | 55.5 | 56.9 | 58.4 | 59.9 |
| 22 | 28.2 | 29.5 | 30.9 | 32.3 | 33.6 | 35.0 | 36.4 | 37.7 | 39.1 | 40.5 | 41.9 | 43.3 | 44.7 | 46.2 | 47.6 | 49.0 | 50.5 | 51.9 | 53.4 | 54.8 | 56.3 | 57.8 | 59.3 | 60.7 | 62.2 |
| 23 | 29.9 | 31.3 | 32.7 | 34.1 | 35.4 | 36.8 | 38.2 | 39.7 | 41.1 | 42.5 | 43.9 | 45.4 | 46.8 | 48.3 | 49.7 | 51.2 | 52.7 | 54.2 | 55.6 | 57.1 | 58.6 | 60.2 | 61.7 | 63.2 | 64.7 |
| 24 | 31.7 | 33.1 | 34.5 | 35.9 | 37.3 | 38.8 | 40.2 | 41.6 | 43.1 | 44.6 | 46.0 | 47.5 | 49.0 | 50.5 | 51.9 | 53.4 | 55.0 | 56.5 | 58.0 | 59.5 | 61.1 | 62.6 | 64.2 | 65.8 | 67.3 |
| 25 | 33.5 | 35.0 | 36.4 | 37.9 | 39.3 | 40.8 | 42.2 | 43.7 | 45.2 | 46.7 | 48.2 | 49.7 | 51.2 | 52.7 | 54.3 | 55.8 | 57.3 | 58.9 | 60.5 | 62.0 | 63.6 | 65.2 | 66.8 | 68.4 | 70.0 |
| 26 | 35.5 | 36.9 | 38.4 | 39.9 | 41.3 | 42.8 | 44.3 | 45.9 | 47.4 | 48.9 | 50.4 | 52.0 | 53.5 | 55.1 | 56.7 | 58.2 | 59.8 | 61.4 | 63.0 | 64.7 | 66.3 | 67.9 | 69.6 | 71.2 | 72.9 |
| 27 | 37.4 | 38.9 | 40.4 | 41.9 | 43.5 | 45.0 | 46.5 | 48.1 | 49.6 | 51.2 | 52.8 | 54.4 | 56.0 | 57.6 | 59.2 | 60.8 | 62.4 | 64.1 | 65.7 | 67.4 | 69.1 | 70.8 | 72.5 | 74.2 | 75.9 |
| 28 | 39.5 | 41.0 | 42.6 | 44.1 | 45.7 | 47.2 | 48.8 | 50.4 | 52.0 | 53.6 | 55.2 | 56.9 | 58.5 | 60.1 | 61.8 | 63.5 | 65.2 | 66.9 | 68.6 | 70.3 | 72.0 | 73.7 | 75.5 | 77.3 | 79.0 |
| 29 | 41.6 | 43.2 | 44.8 | 46.4 | 48.0 | 49.6 | 51.2 | 52.8 | 54.5 | 56.1 | 57.8 | 59.5 | 61.2 | 62.9 | 64.6 | 66.3 | 68.0 | 69.8 | 71.5 | 73.3 | 75.1 | 76.9 | 78.7 | 80.5 | 82.3 |
| 30 | 43.9 | 45.5 | 47.1 | 48.7 | 50.4 | 52.0 | 53.7 | 55.4 | 57.1 | 58.8 | 60.5 | 62.2 | 64.0 | 65.7 | 67.5 | 69.3 | 71.0 | 72.8 | 74.7 | 76.5 | 78.3 | 80.2 | 82.1 | 84.0 | 85.9 |
| 31 | 46.2 | 47.9 | 49.5 | 51.2 | 52.9 | 54.6 | 56.3 | 58.1 | 59.8 | 61.6 | 63.3 | 65.1 | 66.9 | 68.7 | 70.5 | 72.4 | 74.2 | 76.1 | 78.0 | 79.9 | 81.8 | 83.7 | 85.7 | 87.6 | 89.6 |
| 32 | 48.7 | 50.4 | 52.1 | 53.8 | 55.6 | 57.3 | 59.1 | 60.9 | 62.7 | 64.5 | 66.3 | 68.1 | 70.0 | 71.9 | 73.8 | 75.7 | 77.6 | 79.5 | 81.5 | 83.5 | 85.4 | 87.5 | 89.5 | 91.5 | 93.6 |
| 33 | 51.2 | 53.0 | 54.7 | 56.5 | 58.3 | 60.1 | 62.0 | 63.8 | 65.7 | 67.6 | 69.5 | 71.4 | 73.3 | 75.2 | 77.2 | 79.2 | 81.2 | 83.2 | 85.2 | 87.3 | 89.3 | 91.4 | 93.5 | 95.7 | 97.8 |
| 34 | 53.9 | 55.7 | 57.6 | 59.4 | 61.3 | 63.1 | 65.0 | 66.9 | 68.9 | 70.8 | 72.8 | 74.8 | 76.8 | 78.8 | 80.8 | 82.9 | 85.0 | 87.1 | 89.2 | 91.4 | 93.5 | 95.7 | 97.9 | 100.1 | 102.4 |
| 35 | 56.8 | 58.6 | 60.5 | 62.4 | 64.4 | 66.3 | 68.3 | 70.3 | 72.3 | 74.3 | 76.3 | 78.4 | 80.5 | 82.6 | 84.7 | 86.9 | 89.1 | 91.3 | 93.5 | 95.7 | 98.0 | 100.3 | 102.6 | 105.0 | 107.3 |
| 36 | 59.8 | 61.7 | 63.7 | 65.7 | 67.7 | 69.7 | 71.7 | 73.8 | 75.9 | 78.0 | 80.1 | 82.3 | 84.5 | 86.7 | 88.9 | 91.2 | 93.5 | 95.8 | 98.1 | 100.5 | 102.9 | 105.3 | 107.7 | 110.2 | 112.7 |
| 37 | 62.9 | 65.0 | 67.0 | 69.1 | 71.2 | 73.3 | 75.4 | 77.6 | 79.8 | 82.0 | 84.2 | 86.5 | 88.8 | 91.1 | 93.4 | 95.8 | 98.2 | 100.6 | 103.1 | 105.6 | 108.1 | 110.7 | 113.3 | 115.9 | 118.6 |
| 38 | 66.3 | 68.4 | 70.6 | 72.7 | 74.9 | 77.1 | 79.4 | 81.6 | 83.9 | 86.2 | 88.6 | 91.0 | 93.4 | 95.8 | 98.3 | 100.8 | 103.4 | 105.9 | 108.6 | 111.2 | 113.9 | 116.6 | 119.4 | 122.2 | 125.0 |
| 39 | 69.9 | 72.2 | 74.4 | 76.6 | 78.9 | 81.3 | 83.6 | 86.0 | 88.4 | 90.9 | 93.3 | 95.9 | 98.4 | 101.0 | 103.6 | 106.3 | 109.0 | 111.8 | 114.5 | 117.4 | 120.3 | 123.2 | 126.1 | 129.2 | 132.2 |
| 40 | 73.8 | 76.2 | 78.5 | 80.9 | 83.3 | 85.7 | 88.2 | 90.7 | 93.3 | 95.9 | 98.5 | 101.2 | 103.9 | 106.7 | 109.5 | 112.4 | 115.3 | 118.2 | 121.2 | 124.2 | 127.3 | 130.5 | 133.7 | 137.0 | 140.3 |
| 41 | 78.0 | 80.5 | 83.0 | 85.5 | 88.0 | 90.6 | 93.3 | 95.9 | 98.7 | 101.4 | 104.3 | 107.1 | 110.0 | 113.0 | 116.0 | 119.1 | 122.2 | 125.4 | 128.7 | 132.0 | 135.3 | 138.8 | 142.3 | 145.9 | 149.5 |
| 42 | 82.6 | 85.2 | 87.8 | 90.5 | 93.2 | 96.0 | 98.8 | 101.7 | 104.6 | 107.6 | 110.6 | 113.7 | 116.9 | 120.1 | 123.3 | 126.7 | 130.1 | 133.6 | 137.1 | 140.8 | 144.5 | 148.3 | 152.2 | 156.1 | 160.2 |
| 43 | 87.6 | 90.4 | 93.2 | 96.0 | 99.0 | 101.9 | 105.0 | 108.1 | 111.2 | 114.5 | 117.8 | 121.1 | 124.6 | 128.1 | 131.7 | 135.4 | 139.1 | 143.0 | 147.0 | 151.0 | 155.1 | 159.4 | 163.8 | 168.2 | 172.8 |
| 44 | 93.1 | 96.1 | 99.1 | 102.2 | 105.4 | 108.6 | 111.9 | 115.3 | 118.7 | 122.3 | 125.9 | 129.6 | 133.4 | 137.4 | 141.4 | 145.5 | 149.7 | 154.1 | 158.5 | 163.1 | 167.8 | 172.7 | 177.7 | 182.9 | 188.2 |
| 45 | 99.3 | 102.5 | 105.8 | 109.2 | 112.6 | 116.2 | 119.8 | 123.6 | 127.4 | 131.3 | 135.4 | 139.6 | 143.9 | 148.3 | 152.9 | 157.6 | 162.4 | 167.4 | 172.6 | 177.9 | 183.5 | 189.2 | 195.1 | 201.2 | 207.5 |
| 46 | 106.3 | 109.8 | 113.4 | 117.2 | 121.0 | 125.0 | 129.1 | 133.3 | 137.6 | 142.1 | 146.7 | 151.5 | 156.5 | 161.6 | 166.9 | 172.5 | 178.2 | 184.2 | 190.4 | 196.8 | 203.5 | 210.5 | 217.8 | 225.4 | 233.3 |
| 47 | 114.3 | 118.3 | 122.4 | 126.6 | 130.9 | 135.4 | 140.1 | 145.0 | 150.0 | 155.3 | 160.7 | 166.4 | 172.3 | 178.5 | 185.0 | 191.8 | 198.9 | 206.3 | 214.2 | 222.4 | 231.0 | 240.0 | 249.5 | 259.5 | 270.0 |
| 48 | 123.9 | 128.4 | 133.1 | 137.9 | 143.0 | 148.3 | 153.9 | 159.7 | 165.8 | 172.2 | 178.9 | 186.0 | 193.5 | 201.4 | 209.8 | 218.7 | 228.2 | 238.2 | 248.9 | 260.2 | 272.3 | 285.1 | 298.7 | 313.0 | 328.2 |
| 49 | 135.5 | 140.8 | 146.4 | 152.3 | 158.5 | 165.0 | 172.0 | 179.3 | 187.2 | 195.6 | 204.6 | 214.3 | 224.7 | 235.9 | 248.1 | 261.3 | 275.5 | 290.9 | 307.6 | 325.5 | 344.8 | 365.4 | 387.3 | 410.6 | 435.2 |

# IDEXX Quanti-Tray®/2000 MPN Table

| # Large Wells Positive | # Small Wells Positive 25 | 26 | 27 | 28 | 29 | 30 | 31 | 32 | 33 | 34 | 35 | 36 | 37 | 38 | 39 | 40 | 41 | 42 | 43 | 44 | 45 | 46 | 47 | 48 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 25.3 | 26.3 | 27.4 | 28.4 | 29.5 | 30.5 | 31.5 | 32.6 | 33.6 | 34.7 | 35.7 | 36.8 | 37.8 | 38.9 | 39.9 | 41.0 | 42.1 | 43.1 | 44.2 | 45.3 | 46.3 | 47.4 | 48.5 | 49.5 |
| 1 | 26.6 | 27.6 | 28.7 | 29.7 | 30.8 | 31.9 | 32.9 | 34.0 | 35.0 | 36.1 | 37.2 | 38.2 | 39.3 | 40.4 | 41.4 | 42.5 | 43.6 | 44.7 | 45.7 | 46.8 | 47.9 | 49.0 | 50.1 | 51.2 |
| 2 | 27.9 | 29.0 | 30.0 | 31.1 | 32.2 | 33.2 | 34.3 | 35.4 | 36.5 | 37.5 | 38.6 | 39.7 | 40.8 | 41.9 | 42.9 | 44.0 | 45.1 | 46.2 | 47.3 | 48.4 | 49.5 | 50.6 | 51.7 | 52.8 |
| 3 | 29.3 | 30.3 | 31.4 | 32.5 | 33.6 | 34.7 | 35.7 | 36.8 | 37.9 | 39.0 | 40.1 | 41.2 | 42.3 | 43.4 | 44.5 | 45.6 | 46.7 | 47.8 | 48.9 | 50.0 | 51.2 | 52.3 | 53.4 | 54.5 |
| 4 | 30.7 | 31.7 | 32.8 | 33.9 | 35.0 | 36.1 | 37.2 | 38.3 | 39.4 | 40.5 | 41.6 | 42.8 | 43.9 | 45.0 | 46.1 | 47.2 | 48.3 | 49.5 | 50.6 | 51.7 | 52.9 | 54.0 | 55.1 | 56.3 |
| 5 | 32.1 | 33.2 | 34.3 | 35.4 | 36.5 | 37.6 | 38.7 | 39.8 | 41.0 | 42.1 | 43.2 | 44.3 | 45.5 | 46.6 | 47.7 | 48.9 | 50.0 | 51.2 | 52.3 | 53.5 | 54.6 | 55.8 | 56.9 | 58.1 |
| 6 | 33.5 | 34.6 | 35.8 | 36.9 | 38.0 | 39.1 | 40.3 | 41.4 | 42.6 | 43.7 | 44.8 | 46.0 | 47.1 | 48.3 | 49.4 | 50.6 | 51.7 | 52.9 | 54.1 | 55.2 | 56.4 | 57.6 | 58.7 | 59.9 |
| 7 | 35.0 | 36.2 | 37.3 | 38.4 | 39.6 | 40.7 | 41.9 | 43.0 | 44.2 | 45.3 | 46.5 | 47.7 | 48.8 | 50.0 | 51.2 | 52.3 | 53.5 | 54.7 | 55.9 | 57.1 | 58.2 | 59.4 | 60.6 | 61.8 |
| 8 | 36.5 | 37.7 | 38.9 | 40.0 | 41.2 | 42.3 | 43.5 | 44.7 | 45.9 | 47.0 | 48.2 | 49.4 | 50.6 | 51.8 | 53.0 | 54.1 | 55.3 | 56.5 | 57.7 | 58.9 | 60.2 | 61.4 | 62.6 | 63.8 |
| 9 | 38.1 | 39.3 | 40.5 | 41.6 | 42.8 | 44.0 | 45.2 | 46.4 | 47.6 | 48.8 | 50.0 | 51.2 | 52.4 | 53.6 | 54.8 | 56.0 | 57.2 | 58.4 | 59.7 | 60.9 | 62.1 | 63.4 | 64.6 | 65.8 |
| 10 | 39.7 | 40.9 | 42.1 | 43.3 | 44.5 | 45.7 | 46.9 | 48.1 | 49.3 | 50.6 | 51.8 | 53.0 | 54.2 | 55.5 | 56.7 | 57.9 | 59.2 | 60.4 | 61.6 | 62.9 | 64.2 | 65.4 | 66.7 | 67.9 |
| 11 | 41.4 | 42.6 | 43.8 | 45.0 | 46.3 | 47.5 | 48.7 | 49.9 | 51.2 | 52.4 | 53.6 | 54.9 | 56.1 | 57.4 | 58.6 | 59.9 | 61.2 | 62.4 | 63.7 | 65.0 | 66.2 | 67.5 | 68.8 | 70.1 |
| 12 | 43.1 | 44.3 | 45.6 | 46.8 | 48.1 | 49.3 | 50.5 | 51.8 | 53.1 | 54.3 | 55.6 | 56.8 | 58.1 | 59.4 | 60.7 | 61.9 | 63.2 | 64.5 | 65.8 | 67.1 | 68.4 | 69.7 | 71.0 | 72.3 |
| 13 | 44.9 | 46.1 | 47.4 | 48.6 | 49.9 | 51.2 | 52.4 | 53.7 | 55.0 | 56.3 | 57.6 | 58.9 | 60.2 | 61.5 | 62.8 | 64.1 | 65.4 | 66.7 | 68.0 | 69.3 | 70.7 | 72.0 | 73.3 | 74.7 |
| 14 | 46.7 | 48.0 | 49.3 | 50.5 | 51.8 | 53.1 | 54.4 | 55.7 | 57.0 | 58.3 | 59.6 | 60.9 | 62.3 | 63.6 | 64.9 | 66.3 | 67.6 | 68.9 | 70.3 | 71.6 | 73.0 | 74.4 | 75.7 | 77.1 |
| 15 | 48.6 | 49.9 | 51.2 | 52.5 | 53.8 | 55.1 | 56.4 | 57.8 | 59.1 | 60.4 | 61.8 | 63.1 | 64.5 | 65.8 | 67.2 | 68.5 | 69.9 | 71.3 | 72.6 | 74.0 | 75.4 | 76.8 | 78.2 | 79.6 |
| 16 | 50.5 | 51.8 | 53.2 | 54.5 | 55.8 | 57.2 | 58.5 | 59.9 | 61.2 | 62.6 | 64.0 | 65.3 | 66.7 | 68.1 | 69.5 | 70.9 | 72.3 | 73.7 | 75.1 | 76.5 | 77.9 | 79.3 | 80.8 | 82.2 |
| 17 | 52.5 | 53.9 | 55.2 | 56.6 | 58.0 | 59.3 | 60.7 | 62.1 | 63.5 | 64.9 | 66.3 | 67.7 | 69.1 | 70.5 | 71.9 | 73.3 | 74.8 | 76.2 | 77.6 | 79.1 | 80.5 | 82.0 | 83.5 | 84.9 |
| 18 | 54.6 | 56.0 | 57.4 | 58.8 | 60.2 | 61.6 | 63.0 | 64.4 | 65.8 | 67.2 | 68.6 | 70.1 | 71.5 | 73.0 | 74.4 | 75.9 | 77.3 | 78.8 | 80.3 | 81.8 | 83.3 | 84.8 | 86.3 | 87.8 |
| 19 | 56.8 | 58.2 | 59.6 | 61.0 | 62.4 | 63.9 | 65.3 | 66.7 | 68.2 | 69.7 | 71.1 | 72.6 | 74.1 | 75.5 | 77.0 | 78.5 | 80.0 | 81.5 | 83.1 | 84.6 | 86.1 | 87.6 | 89.2 | 90.7 |
| 20 | 59.0 | 60.4 | 61.9 | 63.3 | 64.8 | 66.3 | 67.7 | 69.2 | 70.7 | 72.2 | 73.7 | 75.2 | 76.7 | 78.2 | 79.8 | 81.3 | 82.8 | 84.4 | 85.9 | 87.5 | 89.1 | 90.6 | 92.2 | 93.8 |
| 21 | 61.3 | 62.8 | 64.3 | 65.8 | 67.3 | 68.8 | 70.3 | 71.8 | 73.3 | 74.9 | 76.4 | 77.9 | 79.5 | 81.0 | 82.6 | 84.2 | 85.8 | 87.4 | 89.0 | 90.6 | 92.2 | 93.8 | 95.4 | 97.1 |
| 22 | 63.7 | 65.3 | 66.8 | 68.3 | 69.8 | 71.4 | 72.9 | 74.5 | 76.1 | 77.6 | 79.2 | 80.8 | 82.4 | 84.0 | 85.6 | 87.2 | 88.9 | 90.5 | 92.1 | 93.8 | 95.5 | 97.1 | 98.8 | 100.5 |
| 23 | 66.3 | 67.8 | 69.4 | 71.0 | 72.5 | 74.1 | 75.7 | 77.3 | 78.9 | 80.5 | 82.1 | 83.8 | 85.4 | 87.1 | 88.7 | 90.4 | 92.1 | 93.8 | 95.5 | 97.2 | 98.9 | 100.6 | 102.3 | 104.1 |
| 24 | 68.9 | 70.5 | 72.1 | 73.7 | 75.3 | 77.0 | 78.6 | 80.2 | 81.9 | 83.6 | 85.2 | 86.9 | 88.6 | 90.3 | 92.0 | 93.8 | 95.5 | 97.2 | 99.0 | 100.7 | 102.5 | 104.3 | 106.1 | 107.9 |
| 25 | 71.7 | 73.3 | 75.0 | 76.6 | 78.3 | 80.0 | 81.6 | 83.3 | 85.0 | 86.8 | 88.5 | 90.2 | 92.0 | 93.7 | 95.5 | 97.3 | 99.1 | 100.9 | 102.7 | 104.5 | 106.3 | 108.2 | 110.0 | 111.9 |
| 26 | 74.6 | 76.3 | 78.0 | 79.7 | 81.4 | 83.1 | 84.8 | 86.6 | 88.4 | 90.1 | 91.9 | 93.7 | 95.5 | 97.3 | 99.2 | 101.0 | 102.9 | 104.7 | 106.6 | 108.5 | 110.4 | 112.3 | 114.2 | 116.2 |
| 27 | 77.6 | 79.4 | 81.1 | 82.9 | 84.6 | 86.4 | 88.2 | 90.0 | 91.9 | 93.7 | 95.5 | 97.4 | 99.3 | 101.2 | 103.1 | 105.0 | 106.9 | 108.8 | 110.8 | 112.7 | 114.7 | 116.7 | 118.7 | 120.7 |
| 28 | 80.8 | 82.6 | 84.4 | 86.2 | 88.1 | 89.9 | 91.8 | 93.7 | 95.6 | 97.5 | 99.4 | 101.3 | 103.3 | 105.2 | 107.2 | 109.2 | 111.2 | 113.2 | 115.2 | 117.3 | 119.3 | 121.4 | 123.5 | 125.6 |
| 29 | 84.2 | 86.1 | 87.9 | 89.8 | 91.7 | 93.6 | 95.6 | 97.5 | 99.5 | 101.5 | 103.5 | 105.5 | 107.5 | 109.5 | 111.6 | 113.7 | 115.7 | 117.8 | 120.0 | 122.1 | 124.2 | 126.4 | 128.6 | 130.8 |
| 30 | 87.8 | 89.7 | 91.7 | 93.6 | 95.6 | 97.6 | 99.6 | 101.6 | 103.7 | 105.7 | 107.8 | 109.9 | 112.0 | 114.1 | 116.3 | 118.5 | 120.6 | 122.8 | 125.1 | 127.3 | 129.5 | 131.8 | 134.1 | 136.4 |
| 31 | 91.6 | 93.6 | 95.6 | 97.7 | 99.7 | 101.8 | 103.9 | 106.0 | 108.2 | 110.3 | 112.5 | 114.7 | 116.9 | 119.1 | 121.4 | 123.6 | 125.9 | 128.2 | 130.5 | 132.9 | 135.3 | 137.7 | 140.1 | 142.5 |
| 32 | 95.7 | 97.7 | 99.9 | 102.0 | 104.2 | 106.3 | 108.5 | 110.7 | 113.0 | 115.2 | 117.5 | 119.8 | 122.1 | 124.5 | 126.8 | 129.2 | 131.6 | 134.0 | 136.5 | 139.0 | 141.5 | 144.0 | 146.6 | 149.1 |
| 33 | 100.0 | 102.2 | 104.4 | 106.6 | 108.9 | 111.2 | 113.5 | 115.8 | 118.2 | 120.5 | 122.9 | 125.3 | 127.8 | 130.3 | 132.8 | 135.3 | 137.8 | 140.4 | 143.0 | 145.6 | 148.3 | 150.9 | 153.6 | 156.4 |
| 34 | 104.7 | 107.0 | 109.3 | 111.7 | 114.0 | 116.4 | 118.9 | 121.3 | 123.8 | 126.3 | 128.8 | 131.4 | 134.0 | 136.6 | 139.2 | 141.9 | 144.6 | 147.3 | 150.1 | 152.9 | 155.7 | 158.6 | 161.5 | 164.4 |
| 35 | 109.7 | 112.2 | 114.6 | 117.1 | 119.6 | 122.1 | 124.7 | 127.3 | 129.9 | 132.6 | 135.3 | 138.0 | 140.8 | 143.6 | 146.4 | 149.2 | 152.1 | 155.0 | 158.0 | 161.0 | 164.0 | 167.1 | 170.2 | 173.3 |
| 36 | 115.2 | 117.8 | 120.4 | 123.0 | 125.7 | 128.4 | 131.1 | 133.9 | 136.7 | 139.5 | 142.4 | 145.3 | 148.3 | 151.3 | 154.3 | 157.3 | 160.4 | 163.6 | 166.8 | 170.0 | 173.3 | 176.6 | 179.9 | 183.3 |
| 37 | 121.3 | 124.0 | 126.8 | 129.6 | 132.4 | 135.3 | 138.2 | 141.2 | 144.2 | 147.2 | 150.3 | 153.5 | 156.6 | 159.9 | 163.1 | 166.4 | 169.8 | 173.2 | 176.7 | 180.2 | 183.7 | 187.3 | 191.0 | 194.7 |
| 38 | 127.9 | 130.8 | 133.8 | 136.8 | 139.9 | 143.0 | 146.1 | 149.3 | 152.6 | 155.9 | 159.2 | 162.6 | 166.1 | 169.6 | 173.2 | 176.8 | 180.4 | 184.2 | 188.0 | 191.8 | 195.7 | 199.6 | 203.7 | 207.7 |
| 39 | 135.3 | 138.5 | 141.7 | 145.0 | 148.3 | 151.7 | 155.1 | 158.6 | 162.1 | 165.7 | 169.4 | 173.1 | 176.9 | 180.7 | 184.7 | 188.6 | 192.7 | 196.8 | 201.0 | 205.3 | 209.6 | 214.0 | 218.5 | 223.0 |
| 40 | 143.7 | 147.1 | 150.6 | 154.2 | 157.8 | 161.5 | 165.3 | 169.1 | 173.0 | 177.0 | 181.1 | 185.2 | 189.4 | 193.7 | 198.1 | 202.5 | 207.0 | 211.7 | 216.4 | 221.1 | 226.0 | 231.0 | 236.0 | 241.1 |
| 41 | 153.2 | 157.0 | 160.9 | 164.8 | 168.9 | 173.0 | 177.2 | 181.4 | 185.8 | 190.3 | 194.8 | 199.5 | 204.2 | 209.1 | 214.0 | 219.0 | 224.2 | 229.4 | 234.8 | 240.2 | 245.8 | 251.5 | 257.2 | 263.1 |
| 42 | 164.3 | 168.6 | 172.9 | 177.3 | 181.9 | 186.5 | 191.3 | 196.1 | 201.1 | 206.2 | 211.4 | 216.7 | 222.1 | 227.7 | 233.4 | 239.2 | 245.2 | 251.3 | 257.5 | 263.8 | 270.3 | 276.9 | 283.6 | 290.5 |
| 43 | 177.5 | 182.3 | 187.3 | 192.4 | 197.6 | 202.9 | 208.4 | 214.0 | 219.8 | 225.8 | 231.8 | 238.1 | 244.5 | 251.0 | 257.7 | 264.6 | 271.7 | 278.9 | 286.3 | 293.8 | 301.5 | 309.4 | 317.4 | 325.6 |
| 44 | 193.6 | 199.3 | 205.0 | 211.0 | 217.2 | 223.5 | 230.0 | 236.7 | 243.6 | 250.7 | 258.1 | 265.6 | 273.3 | 281.2 | 289.4 | 297.8 | 306.3 | 315.1 | 324.1 | 333.3 | 342.8 | 352.4 | 362.3 | 372.4 |
| 45 | 214.1 | 220.9 | 227.9 | 235.1 | 242.7 | 250.4 | 258.4 | 266.7 | 275.3 | 284.1 | 293.2 | 302.6 | 312.3 | 322.3 | 332.5 | 343.0 | 353.8 | 364.9 | 376.2 | 387.9 | 399.8 | 412.0 | 424.5 | 437.4 |
| 46 | 241.5 | 250.0 | 258.9 | 268.2 | 277.8 | 287.7 | 298.1 | 308.8 | 319.9 | 331.4 | 343.3 | 355.5 | 368.1 | 381.1 | 394.5 | 408.3 | 422.5 | 437.0 | 452.0 | 467.4 | 483.3 | 499.5 | 516.3 | 533.5 |
| 47 | 280.9 | 292.4 | 304.4 | 316.9 | 330.0 | 343.6 | 357.8 | 372.5 | 387.7 | 403.4 | 419.8 | 436.6 | 454.1 | 472.1 | 490.7 | 509.9 | 529.8 | 550.4 | 571.7 | 593.8 | 616.7 | 640.5 | 665.3 | 691.0 |
| 48 | 344.1 | 360.9 | 378.4 | 396.8 | 416.0 | 436.0 | 456.9 | 478.6 | 501.2 | 524.7 | 549.2 | 574.8 | 601.5 | 629.4 | 658.6 | 689.3 | 721.5 | 755.5 | 791.5 | 829.7 | 870.4 | 913.9 | 960.6 | 1011.1 |
| 49 | 461.1 | 488.4 | 517.2 | 547.5 | 579.4 | 613.1 | 648.8 | 686.7 | 727.0 | 770.1 | 816.4 | 866.4 | 920.8 | 980.4 | 1046.2 | 1119.9 | 1203.3 | 1299.7 | 1413.6 | 1553.1 | 1732.9 | 1986.3 | 2419.2 | >2419.2 |

# APPENDIX H: Experimental Results

## *H.1: Daily Average Head Losses*

**Table H.1** Head Losses During Run 1

(Head Loss Unit - mm)

| Date | Day | Filter 1 | Filter 2 | | | Filter 3 | | | Filter 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Total | Fabric | Sand | Total | Fabric | Sand | Total | Fabric | Sand |
| 6-Jan | **0** | 22 | 22 | 0 | 22 | 21 | 0 | 21 | 23 | 0 | 23 |
| 7-Jan | **1** | 32 | 23 | 4 | 19 | 23 | 3 | 20 | 26 | 5 | 21 |
| 8-Jan | **2** | 35 | 28 | 6 | 22 | 27 | 6 | 21 | 34 | 11 | 23 |
| 9-Jan | **3** | 58 | 46 | 21 | 25 | 42 | 21 | 21 | 52 | 28 | 24 |
| 10-Jan | **4** | 50 | 39 | 14 | 25 | 36 | 16 | 20 | 40 | 19 | 21 |
| 11-Jan | **5** | 66 | 48 | 28 | 20 | 57 | 36 | 21 | 62 | 41 | 21 |
| 12-Jan | **6** | 138 | 108 | 60 | 48 | 107 | 87 | 20 | 108 | 88 | 20 |
| 13-Jan | **7** | 211 | 163 | 82 | 81 | 170 | 150 | 20 | 165 | 147 | 18 |
| 14-Jan | **8** | 257 | 225 | 96 | 129 | 218 | 197 | 21 | 211 | 191 | 20 |
| 15-Jan | **9** | 357 | 304 | 134 | 170 | 308 | 286 | 22 | 274 | 254 | 20 |
| 16-Jan | **10** | 455 | 387 | 187 | 200 | 383 | 359 | 24 | 319 | 299 | 20 |
| 17-Jan | **11** | 574 | 455 | 202 | 253 | 463 | 436 | 27 | 416 | 394 | 22 |
| 18-Jan | **12** | 667 | 507 | 220 | 287 | 549 | 511 | 38 | 485 | 464 | 21 |
| 19-Jan | **13** | 759 | 560 | 267 | 293 | 668 | 634 | 34 | 627 | 608 | 19 |
| 20-Jan | **14** | 769 | 571 | 302 | 269 | 734 | 678 | 56 | 686 | 665 | 21 |
| 21-Jan | **15** | 817 | 626 | 330 | 296 | 782 | 716 | 66 | 744 | 724 | 20 |
| 22-Jan | **16** | 924 | 733 | 407 | 326 | 970 | 855 | 115 | 970 | 948 | 22 |
| 23-Jan | **17** | 963 | 775 | 439 | 336 | 983 | 856 | 127 | 1004 | 985 | 19 |
| 24-Jan | **18** | 982 | 811 | 430 | 381 | 997 | 852 | 145 | 1020 | 999 | 21 |
| 25-Jan | **19** | 991 | 860 | 429 | 431 | 1015 | 855 | 160 | 1036 | 1015 | 21 |
| 26-Jan | **20** | 1005 | 966 | 460 | 506 | 1040 | 877 | 163 | 1050 | 1038 | 22 |

**Table H.2** Head Losses During Run 2

(Head Loss Unit - mm)

| Date | Day | Filter 1 | Filter 2 | | | Filter 3 | | | Filter 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Total | Fabric | Sand | Total | Fabric | Sand | Total | Fabric | Sand |
| 4-Mar | **0** | 18 | 20 | 1 | 19 | 17 | 0 | 17 | 20 | 0 | 20 |
| 5-Mar | **1** | 18 | 18 | 0 | 18 | 17 | 1 | 16 | 21 | 0 | 21 |
| 6-Mar | **2** | 19 | 19 | 1 | 18 | 17 | 0 | 17 | 21 | 0 | 21 |
| 7-Mar | **3** | 21 | 19 | 0 | 19 | 18 | 1 | 17 | 20 | 0 | 20 |
| 8-Mar | **4** | 24 | 18 | 0 | 18 | 19 | 1 | 18 | 21 | 0 | 21 |
| 9-Mar | **5** | 23 | 19 | 1 | 18 | 18 | 0 | 18 | 22 | 0 | 22 |
| 10-Mar | **6** | 21 | 18 | 0 | 18 | 18 | 0 | 18 | 20 | 0 | 20 |
| 11-Mar | **7** | 23 | 18 | 0 | 18 | 19 | 0 | 19 | 20 | 0 | 20 |
| 12-Mar | **8** | 23 | 18 | 0 | 18 | 19 | 0 | 19 | 19 | 0 | 19 |
| 13-Mar | **9** | 24 | 18 | 0 | 18 | 19 | 0 | 19 | 18 | 0 | 18 |
| 14-Mar | **10** | 25 | 19 | 1 | 18 | 19 | 1 | 18 | 18 | 0 | 18 |
| 15-Mar | **11** | 26 | 20 | 0 | 20 | 19 | 0 | 19 | 16 | 0 | 16 |
| 16-Mar | **12** | 30 | 19 | 0 | 19 | 18 | 0 | 18 | 16 | 0 | 16 |
| 17-Mar | **13** | 34 | 18 | 1 | 17 | 19 | 0 | 19 | 16 | 0 | 16 |
| 18-Mar | **14** | 37 | 18 | 0 | 18 | 19 | 0 | 19 | 18 | 0 | 18 |
| 19-Mar | **15** | 41 | 20 | 0 | 20 | 19 | 0 | 19 | 18 | 0 | 18 |
| 20-Mar | **16** | 43 | 20 | 1 | 19 | 18 | 1 | 17 | 21 | 0 | 21 |
| 21-Mar | **17** | 47 | 19 | 1 | 18 | 19 | 0 | 19 | 23 | 0 | 23 |
| 22-Mar | **18** | 53 | 20 | 0 | 20 | 19 | 0 | 19 | 24 | 0 | 24 |
| 23-Mar | **19** | 66 | 21 | 0 | 21 | 20 | 1 | 19 | 23 | 0 | 23 |
| 24-Mar | **20** | 72 | 21 | 0 | 21 | 19 | 1 | 18 | 23 | 0 | 23 |
| 25-Mar | **21** | 81 | 22 | 1 | 21 | 19 | 2 | 17 | 23 | 0 | 23 |
| 26-Mar | **22** | 86 | 22 | 1 | 21 | 18 | 0 | 18 | 21 | 0 | 21 |
| 27-Mar | **23** | 113 | 23 | 3 | 20 | 21 | 3 | 18 | 26 | 2 | 24 |
| 28-Mar | **24** | 128 | 24 | 2 | 22 | 22 | 2 | 20 | 27 | 2 | 25 |
| 29-Mar | **25** | 134 | 25 | 4 | 21 | 26 | 6 | 20 | 30 | 4 | 26 |
| 30-Mar | **26** | 137 | 25 | 3 | 22 | 25 | 5 | 20 | 29 | 4 | 25 |
| 31-Mar | **27** | 156 | 23 | 2 | 21 | 26 | 6 | 20 | 28 | 4 | 24 |
| 1-Apr | **28** | 178 | 26 | 4 | 22 | 27 | 5 | 22 | 28 | 4 | 24 |
| 2-Apr | **29** | 185 | 27 | 5 | 22 | 26 | 6 | 20 | 28 | 4 | 24 |
| 3-Apr | **30** | 208 | 29 | 7 | 22 | 26 | 6 | 20 | 29 | 5 | 24 |

**Table H.2** Continued

| Date | Day | Filter 1 | Filter 2 | | | Filter 3 | | | Filter 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Total | Fabric | Sand | Total | Fabric | Sand | Total | Fabric | Sand |
| 4-Apr | **31** | 199 | 30 | 8 | 22 | 26 | 6 | 20 | 30 | 5 | 25 |
| 5-Apr | **32** | 206 | 34 | 11 | 23 | 27 | 7 | 20 | 32 | 7 | 25 |
| 6-Apr | **33** | 217 | 42 | 17 | 25 | 28 | 7 | 21 | 33 | 8 | 25 |
| 7-Apr | **34** | 223 | 49 | 25 | 24 | 30 | 9 | 21 | 37 | 11 | 26 |
| 8-Apr | **35** | 241 | 48 | 24 | 24 | 28 | 9 | 19 | 34 | 10 | 24 |
| 9-Apr | **36** | 266 | 48 | 24 | 24 | 27 | 8 | 19 | 32 | 8 | 24 |
| 10-Apr | **37** | 371 | 109 | 79 | 30 | 115 | 95 | 20 | 98 | 76 | 22 |
| 11-Apr | **38** | 477 | 203 | 169 | 34 | 193 | 170 | 23 | 175 | 154 | 21 |
| 12-Apr | **39** | 285 | 113 | 90 | 23 | 87 | 64 | 23 | 60 | 38 | 22 |
| 13-Apr | **40** | 180 | 49 | 21 | 28 | 36 | 13 | 23 | 23 | 2 | 21 |
| 14-Apr | **41** | 152 | 43 | 19 | 24 | 33 | 11 | 22 | 23 | 2 | 21 |
| 15-Apr | **42** | 103 | 39 | 17 | 22 | 32 | 11 | 21 | 24 | 3 | 21 |
| 16-Apr | **43** | 93 | 37 | 14 | 23 | 29 | 9 | 20 | 23 | 3 | 20 |
| 17-Apr | **44** | 76 | 38 | 14 | 24 | 27 | 7 | 20 | 22 | 1 | 21 |
| 18-Apr | **45** | 86 | 46 | 23 | 23 | 28 | 7 | 21 | 25 | 1 | 24 |
| 19-Apr | **46** | 86 | 64 | 25 | 39 | 28 | 6 | 22 | 26 | 1 | 25 |
| 20-Apr | **47** | 95 | 72 | 25 | 47 | 25 | 4 | 21 | 24 | 2 | 22 |
| 21-Apr | **48** | 98 | 80 | 17 | 63 | 26 | 3 | 23 | 23 | 0 | 23 |
| 22-Apr | **49** | 132 | 80 | 16 | 64 | 33 | 3 | 30 | 32 | 3 | 29 |
| 23-Apr | **50** | 290 | 132 | 73 | 59 | 52 | 20 | 32 | 51 | 23 | 28 |
| 24-Apr | **51** | 331 | 150 | 73 | 77 | 86 | 52 | 34 | 57 | 29 | 28 |
| 25-Apr | **52** | 398 | 189 | 88 | 101 | 119 | 78 | 41 | 115 | 88 | 27 |
| 26-Apr | **53** | 425 | 199 | 86 | 113 | 134 | 91 | 43 | 152 | 135 | 17 |
| 27-Apr | **54** | 460 | 287 | 178 | 109 | 245 | 200 | 45 | 264 | 238 | 26 |
| 28-Apr | **55** | 514 | 369 | 228 | 141 | 330 | 291 | 39 | 351 | 329 | 22 |
| 29-Apr | **56** | 566 | 440 | 286 | 154 | 433 | 383 | 50 | 486 | 466 | 20 |
| 30-Apr | **57** | 864 | 568 | 415 | 153 | 632 | 585 | 47 | 689 | 662 | 27 |
| 1-May | **58** | 1001 | 776 | 593 | 183 | 888 | 854 | 34 | 959 | 931 | 28 |
| 2-May | **59** | 999 | 820 | 635 | 185 | 887 | 856 | 31 | 966 | 942 | 24 |
| 3-May | **60** | 1001 | 857 | 662 | 195 | 916 | 891 | 25 | 986 | 963 | 23 |
| 4-May | **61** | 1004 | 913 | 702 | 211 | 954 | 927 | 27 | 1002 | 977 | 25 |

**Table H.3:** Head Losses During Run 3

(Head Loss Unit - mm)

| Date | Day | Filter 1 | Filter 2 | | | Filter 3 | | | Filter 4 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | Total | Fabric | Sand | Total | Fabric | Sand | Total | Fabric | Sand |
| 6-May | **0** | 43 | 21 | 1 | 20 | 23 | 1 | 22 | 23 | 1 | 22 |
| 7-May | **1** | 114 | 58 | 29 | 29 | 72 | 48 | 24 | 71 | 49 | 22 |
| 8-May | **2** | 57 | 76 | 51 | 25 | 76 | 54 | 22 | 79 | 58 | 21 |
| 9-May | **3** | 140 | 121 | 98 | 23 | 110 | 88 | 22 | 174 | 156 | 18 |
| 10-May | **4** | 220 | 155 | 134 | 21 | 216 | 192 | 24 | 229 | 210 | 19 |
| 11-May | **5** | 193 | 166 | 143 | 23 | 243 | 215 | 28 | 320 | 300 | 20 |
| 12-May | **6** | 590 | 552 | 531 | 21 | 540 | 517 | 23 | 757 | 736 | 21 |
| 13-May | **7** | 603 | 564 | 542 | 22 | 604 | 583 | 21 | 788 | 766 | 22 |
| 14-May | **8** | 872 | 780 | 758 | 22 | 848 | 828 | 20 | 975 | 955 | 20 |
| 15-May | **9** | 861 | 777 | 755 | 22 | 850 | 824 | 26 | 984 | 964 | 20 |
| 16-May | **10** | 878 | 956 | 928 | 28 | 941 | 913 | 28 | 1013 | 993 | 20 |

### *H.2: Feed and Filtrate Water Turbidity*

**Table H.4:** Turbidity Removal Efficiencies of Filters (Run 1)

(Turbidity Unit - NTU)

| Day | Feed* | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| **0** | | | | | | | | | | | | | | | |
| **1** | 11 | 0.25 | 97.7 | 0.30 | 97.3 | 4.30 | 60.9 | 0.30 | 97.3 | 0.75 | 93.2 | 0.25 | 97.7 | 0.35 | 96.8 |
| **2** | 9.9 | 0.20 | 98.0 | 0.20 | 98.0 | 2.40 | 75.8 | 0.20 | 98.0 | 0.65 | 93.4 | 0.15 | 98.5 | 0.30 | 97.0 |
| **3** | 11 | 0.30 | 97.3 | 0.15 | 98.6 | 3.60 | 67.3 | 0.20 | 98.2 | 0.85 | 92.3 | 0.20 | 98.2 | 0.25 | 97.7 |
| **4** | 9.5 | 0.30 | 96.8 | 0.20 | 97.9 | 2.30 | 75.8 | 0.20 | 97.9 | 0.75 | 92.1 | 0.20 | 97.9 | 0.35 | 96.3 |
| **5** | 11 | 0.15 | 98.6 | 0.25 | 97.7 | 2.40 | 78.2 | 0.15 | 98.6 | 0.55 | 95.0 | 0.15 | 98.6 | 0.30 | 97.3 |
| **6** | 11 | 0.25 | 97.7 | 0.10 | 99.1 | 2.10 | 80.9 | 0.20 | 98.2 | 0.45 | 95.9 | 0.15 | 98.6 | 0.25 | 97.7 |
| **7** | 10 | 0.20 | 98.0 | 0.15 | 98.5 | 3.40 | 66.0 | 0.15 | 98.5 | 0.40 | 96.0 | 0.10 | 99.0 | 0.25 | 97.5 |
| **8** | 10 | 0.25 | 97.5 | 0.15 | 98.5 | 3.00 | 70.0 | 0.10 | 99.0 | 0.45 | 95.5 | 0.15 | 98.5 | 0.20 | 98.0 |
| **9** | 9.5 | 0.20 | 97.9 | 0.15 | 98.4 | 4.00 | 57.9 | 0.15 | 98.4 | 0.35 | 96.3 | 0.10 | 98.9 | 0.15 | 98.4 |
| **10** | 12 | 0.15 | 98.8 | 0.15 | 98.8 | 2.40 | 80.0 | 0.15 | 98.8 | 0.35 | 97.1 | 0.10 | 99.2 | 0.20 | 98.4 |
| **11** | 10 | 0.20 | 98.0 | 0.15 | 98.5 | 1.90 | 81.0 | 0.10 | 99.0 | 0.40 | 96.0 | 0.10 | 99.0 | 0.20 | 98.0 |
| **12** | 9.7 | 0.20 | 97.9 | 0.15 | 98.5 | 3.20 | 67.0 | 0.15 | 98.5 | 0.45 | 95.4 | 0.15 | 98.5 | 0.25 | 97.4 |
| **13** | 11 | 0.15 | 98.6 | 0.15 | 98.6 | 2.20 | 80.0 | 0.15 | 98.6 | 0.35 | 96.8 | 0.15 | 98.6 | 0.20 | 98.2 |
| **14** | 11 | 0.15 | 98.6 | 0.20 | 98.2 | 2.60 | 76.4 | 0.15 | 98.6 | 0.40 | 96.4 | 0.10 | 99.1 | 0.15 | 98.6 |
| **15** | 12 | 0.20 | 98.3 | 0.15 | 98.8 | 2.70 | 77.5 | 0.15 | 98.8 | 0.35 | 97.1 | 0.10 | 99.2 | 0.15 | 98.8 |
| **16** | 12 | 0.15 | 98.8 | 0.10 | 99.2 | 2.60 | 78.3 | 0.10 | 99.2 | 0.20 | 98.3 | 0.10 | 99.2 | 0.15 | 98.8 |
| **17** | 12 | 0.15 | 98.8 | 0.15 | 98.8 | 2.20 | 81.7 | 0.10 | 99.2 | 0.20 | 98.3 | 0.10 | 99.2 | 0.20 | 98.3 |
| **18** | 10 | 0.10 | 99.0 | 0.10 | 99.0 | 2.60 | 74.0 | 0.10 | 99.0 | 0.15 | 98.5 | 0.10 | 99.0 | 0.15 | 98.5 |
| **19** | 9.6 | 0.15 | 98.4 | 0.15 | 98.4 | 2.20 | 77.1 | 0.10 | 99.0 | 0.10 | 99.0 | 0.10 | 99.0 | 0.10 | 99.0 |
| **20** | 11 | 0.10 | 99.1 | 0.15 | 98.6 | 1.90 | 82.7 | 0.10 | 99.1 | 0.15 | 98.6 | 0.10 | 99.1 | 0.10 | 99.1 |
| **Average** | **11** | **0.20** | **98.1** | **0.15** | **98.5** | **2.70** | **74.4** | **0.15** | **98.6** | **0.40** | **96.1** | **0.15** | **98.7** | **0.20** | **98.0** |
| **Sample** | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| **St. Dev.** | **0.89** | **0.06** | **0.60** | **0.05** | **0.47** | **0.68** | **7.16** | **0.05** | **0.49** | **0.21** | **2.07** | **0.04** | **0.43** | **0.07** | **0.76** |
| **Highest** | **12.00** | **0.30** | **99.1** | **0.30** | **99.2** | **4.30** | **82.7** | **0.30** | **99.2** | **0.85** | **99.0** | **0.25** | **99.2** | **0.35** | **99.1** |
| **Lowest** | **9.50** | **0.10** | **96.8** | **0.10** | **97.3** | **1.90** | **57.9** | **0.10** | **97.3** | **0.10** | **92.1** | **0.10** | **97.7** | **0.10** | **96.3** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. **St. Dev.** - Standard deviation.

**Table H.5:** Turbidity Removal Efficiencies of Filters (Run 2)

(Turbidity Unit – NTU)

| Day | Feed* | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Faric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 0 | | | | | | | | | | | | | | | |
| 1 | 1.4 | 0.55 | 60.7 | 0.65 | 53.6 | 1.20 | 14.3 | 0.70 | 50.0 | 1.10 | 21.4 | 0.80 | 42.9 | 0.95 | 32.1 |
| 2 | 1.4 | 0.65 | 53.6 | 0.55 | 60.7 | 1.10 | 21.4 | 0.65 | 53.6 | 0.90 | 35.7 | 0.60 | 57.1 | 0.85 | 39.3 |
| 3 | 1.6 | 0.70 | 56.3 | 0.50 | 68.8 | 1.20 | 25.0 | 0.70 | 56.3 | 0.85 | 46.9 | 0.65 | 59.4 | 0.75 | 53.1 |
| 4 | 1.6 | 0.55 | 65.6 | 0.70 | 56.3 | 0.95 | 40.6 | 0.55 | 65.6 | 0.85 | 46.9 | 0.55 | 65.6 | 0.70 | 56.3 |
| 5 | 1.8 | 0.45 | 75.0 | 0.78 | 56.7 | 0.95 | 47.2 | 0.60 | 66.7 | 1.10 | 38.9 | 0.55 | 69.4 | 0.85 | 52.8 |
| 6 | 1.5 | 0.85 | 43.3 | 0.55 | 63.3 | 0.90 | 40.0 | 0.50 | 66.7 | 0.85 | 43.3 | 0.55 | 63.3 | 0.75 | 50.0 |
| 7 | 1.6 | 0.45 | 71.9 | 0.40 | 75.0 | 1.40 | 12.5 | 0.45 | 71.9 | 0.75 | 53.1 | 0.40 | 75.0 | 0.65 | 59.4 |
| 8 | 1.8 | 0.40 | 77.8 | 0.25 | 86.1 | 1.10 | 38.9 | 0.35 | 80.6 | 0.65 | 63.9 | 0.40 | 77.8 | 0.70 | 61.1 |
| 9 | 1.9 | 0.60 | 68.4 | 0.35 | 81.6 | 0.90 | 52.6 | 0.65 | 65.8 | 0.75 | 60.5 | 0.65 | 65.8 | 0.85 | 55.3 |
| 10 | 2 | 0.80 | 60.0 | 0.45 | 77.5 | 0.75 | 62.5 | 0.55 | 72.5 | 0.70 | 65.0 | 0.50 | 75.0 | 0.55 | 72.5 |
| 11 | 1.5 | 0.35 | 76.7 | 0.40 | 73.3 | 0.95 | 36.7 | 0.65 | 56.7 | 0.65 | 56.7 | 0.55 | 63.3 | 0.60 | 60.0 |
| 12 | 1.6 | 0.75 | 53.1 | 0.60 | 62.5 | 1.10 | 31.3 | 0.45 | 71.9 | 0.70 | 56.3 | 0.35 | 78.1 | 0.55 | 65.6 |
| 13 | 1.4 | 0.70 | 50.0 | 0.70 | 50.0 | 1.10 | 21.4 | 0.35 | 75.0 | 0.85 | 39.3 | 0.25 | 82.1 | 0.45 | 67.9 |
| 14 | 1.8 | 0.55 | 69.4 | 0.45 | 75.0 | 1.40 | 22.2 | 0.45 | 75.0 | 0.60 | 66.7 | 0.35 | 80.6 | 0.40 | 77.8 |
| 15 | 1.9 | 0.65 | 65.8 | 0.70 | 63.2 | 1.30 | 31.6 | 0.40 | 78.9 | 0.50 | 73.7 | 0.35 | 81.6 | 0.45 | 76.3 |
| 16 | 1.6 | 0.40 | 75.0 | 0.50 | 68.8 | 1.10 | 31.3 | 0.45 | 71.9 | 0.45 | 71.9 | 0.25 | 84.4 | 0.30 | 81.3 |
| 17 | 1.7 | 0.60 | 64.7 | 0.55 | 67.6 | 0.95 | 44.1 | 0.55 | 67.6 | 0.65 | 61.8 | 0.15 | 91.2 | 0.30 | 82.4 |
| 18 | 1.5 | 0.50 | 66.7 | 0.45 | 70.0 | 0.80 | 46.7 | 0.45 | 70.0 | 0.50 | 66.7 | 0.25 | 83.3 | 0.45 | 70.0 |
| 19 | 1.5 | 0.30 | 80.0 | 0.65 | 56.7 | 0.85 | 43.3 | 0.50 | 66.7 | 0.60 | 60.0 | 0.35 | 76.7 | 0.50 | 66.7 |
| 20 | 1.6 | 0.25 | 84.4 | 0.75 | 53.1 | 0.75 | 53.1 | 0.40 | 75.0 | 0.45 | 71.9 | 0.30 | 81.3 | 0.40 | 75.0 |
| 21 | 1.4 | 0.40 | 71.4 | 0.70 | 50.0 | 0.85 | 39.3 | 0.35 | 75.0 | 0.50 | 64.3 | 0.35 | 75.0 | 0.55 | 60.7 |
| 22 | 1.8 | 0.70 | 61.1 | 0.65 | 63.9 | 1.20 | 33.3 | 0.45 | 75.0 | 0.65 | 63.9 | 0.35 | 80.6 | 0.45 | 75.0 |
| 23 | 1.8 | 0.60 | 66.7 | 0.45 | 75.0 | 1.10 | 38.9 | 0.30 | 83.3 | 0.45 | 75.0 | 0.20 | 88.9 | 0.30 | 83.3 |
| 24 | 2 | 0.65 | 67.5 | 0.55 | 72.5 | 1.30 | 35.0 | 0.35 | 82.5 | 0.40 | 80.0 | 0.15 | 92.5 | 0.30 | 85.0 |
| 25 | 1.9 | 0.75 | 60.5 | 0.80 | 57.9 | 1.10 | 42.1 | 0.25 | 86.8 | 0.50 | 73.7 | 0.25 | 86.8 | 0.40 | 78.9 |

**Table H.5:** Continued

| Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Faric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| **26** | 1.7 | 0.60 | 64.7 | 0.65 | 61.8 | 1.00 | 41.2 | 0.35 | 79.4 | 0.75 | 55.9 | 0.35 | 79.4 | 0.40 | 76.5 |
| **27** | 1.6 | 0.55 | 65.6 | 0.45 | 71.9 | 1.00 | 37.5 | 0.40 | 75.0 | 0.40 | 75.0 | 0.20 | 87.5 | 0.30 | 81.3 |
| **28** | 1.6 | 0.45 | 71.9 | 0.40 | 75.0 | 0.95 | 40.6 | 0.45 | 71.9 | 0.60 | 62.5 | 0.35 | 78.1 | 0.45 | 71.9 |
| **29** | 1.7 | 0.65 | 61.8 | 0.55 | 67.6 | 0.75 | 55.9 | 0.50 | 70.6 | 0.75 | 55.9 | 0.30 | 82.4 | 0.50 | 70.6 |
| **30** | 1.4 | 0.70 | 50.0 | 0.70 | 50.0 | 0.85 | 39.3 | 0.45 | 67.9 | 0.50 | 64.3 | 0.40 | 71.4 | 0.60 | 57.1 |
| **31** | 1.9 | 0.45 | 76.3 | 0.45 | 76.3 | 0.65 | 65.8 | 0.35 | 81.6 | 0.45 | 76.3 | 0.40 | 78.9 | 0.65 | 65.8 |
| **32** | 1.4 | 0.75 | 46.4 | 0.55 | 60.7 | 0.75 | 46.4 | 0.50 | 64.3 | 0.50 | 64.3 | 0.35 | 75.0 | 0.50 | 64.3 |
| **33** | 1.8 | 0.65 | 63.9 | 0.45 | 75.0 | 0.70 | 61.1 | 0.30 | 83.3 | 0.65 | 63.9 | 0.35 | 80.6 | 0.40 | 77.8 |
| **34** | 1.8 | 0.45 | 75.0 | 0.40 | 77.8 | 0.80 | 55.6 | 0.20 | 88.9 | 0.40 | 77.8 | 0.25 | 86.1 | 0.40 | 77.8 |
| **35** | 1.7 | 0.40 | 76.5 | 0.55 | 67.6 | 0.85 | 50.0 | 0.50 | 70.6 | 0.65 | 61.8 | 0.50 | 70.6 | 0.50 | 70.6 |
| **36** | 1.9 | 0.65 | 65.8 | 0.65 | 65.8 | 0.75 | 60.5 | 0.55 | 71.1 | 0.70 | 63.2 | 0.40 | 78.9 | 0.55 | 71.1 |
| **37** | 2 | 0.70 | 65.0 | 0.75 | 62.5 | 1.30 | 35.0 | 0.45 | 77.5 | 0.75 | 62.5 | 0.45 | 77.5 | 0.50 | 75.0 |
| **38** | 1.7 | 0.65 | 61.8 | 0.75 | 55.9 | 1.10 | 35.3 | 0.60 | 64.7 | 0.80 | 52.9 | 0.45 | 73.5 | 0.60 | 64.7 |
| **39** | 1.5 | 0.85 | 43.3 | 0.55 | 63.3 | 1.30 | 13.3 | 0.70 | 53.3 | 0.85 | 43.3 | 0.50 | 66.7 | 0.70 | 53.3 |
| **40** | 1.6 | 0.75 | 53.1 | 0.65 | 59.4 | 1.00 | 37.5 | 0.85 | 46.9 | 0.95 | 40.6 | 0.65 | 59.4 | 0.80 | 50.0 |
| **41** | 1.9 | 1.00 | 47.4 | 0.85 | 55.3 | 1.10 | 42.1 | 0.75 | 60.5 | 0.80 | 57.9 | 0.75 | 60.5 | 0.85 | 55.3 |
| **42** | 1.4 | 0.75 | 46.4 | 0.80 | 42.9 | 0.85 | 39.3 | 0.65 | 53.6 | 0.90 | 35.7 | 0.65 | 53.6 | 0.70 | 50.0 |
| **43** | 1.6 | 0.65 | 59.4 | 0.75 | 53.1 | 0.75 | 53.1 | 0.70 | 56.3 | 0.85 | 46.9 | 0.50 | 68.8 | 0.75 | 53.1 |
| **44** | 1.8 | 0.90 | 50.0 | 0.65 | 63.9 | 0.80 | 55.6 | 0.65 | 63.9 | 0.75 | 58.3 | 0.45 | 75.0 | 0.70 | 61.1 |
| **45** | 1.9 | 0.85 | 55.3 | 0.55 | 71.1 | 1.00 | 47.4 | 0.55 | 71.1 | 0.75 | 60.5 | 0.40 | 78.9 | 0.60 | 68.4 |
| **46** | 1.4 | 1.10 | 21.4 | 0.55 | 60.7 | 0.95 | 32.1 | 0.45 | 67.9 | 0.70 | 50.0 | 0.45 | 67.9 | 0.55 | 60.7 |
| **47** | 1.6 | 0.75 | 53.1 | 0.65 | 59.4 | 0.95 | 40.6 | 0.75 | 53.1 | 0.85 | 46.9 | 0.50 | 68.8 | 0.70 | 56.3 |
| **48** | 1.9 | 0.80 | 57.9 | 0.45 | 76.3 | 0.75 | 60.5 | 0.85 | 55.3 | 0.90 | 52.6 | 0.75 | 60.5 | 0.85 | 55.3 |
| **49** | 1.8 | 0.65 | 63.9 | 0.75 | 58.3 | 1.00 | 44.4 | 0.90 | 50.0 | 1.20 | 33.3 | 0.60 | 66.7 | 0.75 | 58.3 |
| **50** | 1.9 | 0.75 | 60.5 | 0.80 | 57.9 | 0.85 | 55.3 | 0.80 | 57.9 | 0.90 | 52.6 | 0.75 | 60.5 | 0.75 | 60.5 |

**Table H.5:** Continued

| Day | Feed (16h) | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total | % Rem. | Total | % Rem. | Faric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| | | | | | | | | | | | | | | | |
| **51** | 2 | 0.65 | 67.5 | 0.85 | 57.5 | 0.95 | 52.5 | 0.85 | 57.5 | 0.85 | 57.5 | 0.80 | 60.0 | 0.95 | 52.5 |
| **52** | 2 | 0.90 | 55.0 | 0.85 | 57.5 | 1.10 | 45.0 | 0.75 | 62.5 | 0.85 | 57.5 | 0.90 | 55.0 | 1.10 | 45.0 |
| **53** | 1.8 | 1.10 | 38.9 | 0.85 | 52.8 | 1.10 | 38.9 | 0.85 | 52.8 | 0.90 | 50.0 | 1.00 | 44.4 | 1.20 | 33.3 |
| **54** | 1.7 | 0.75 | 55.9 | 0.85 | 50.0 | 0.95 | 44.1 | 0.85 | 50.0 | 1.00 | 41.2 | 0.85 | 50.0 | 1.10 | 35.3 |
| **55** | 1.6 | 1.20 | 25.0 | 0.90 | 43.8 | 1.20 | 25.0 | 1.10 | 31.3 | 1.20 | 25.0 | 0.90 | 43.8 | 0.95 | 40.6 |
| **56** | 1.8 | 1.10 | 38.9 | 1.20 | 33.3 | 1.10 | 38.9 | 0.85 | 52.8 | 1.10 | 38.9 | 0.85 | 52.8 | 0.90 | 50.0 |
| **57** | 1.5 | 0.85 | 43.3 | 0.85 | 43.3 | 1.20 | 20.0 | 0.80 | 46.7 | 1.00 | 33.3 | 0.65 | 56.7 | 0.85 | 43.3 |
| **58** | 1.9 | 0.70 | 63.2 | 0.85 | 55.3 | 1.10 | 42.1 | 0.70 | 63.2 | 0.85 | 55.3 | 0.70 | 63.2 | 0.85 | 55.3 |
| **59** | 1.4 | 0.60 | 57.1 | 0.65 | 53.6 | 0.85 | 39.3 | 0.65 | 53.6 | 0.90 | 35.7 | 0.50 | 64.3 | 0.85 | 39.3 |
| **60** | 1.7 | 0.65 | 61.8 | 0.50 | 70.6 | 0.85 | 50.0 | 0.65 | 61.8 | 0.85 | 50.0 | 0.50 | 70.6 | 0.75 | 55.9 |
| **61** | 1.6 | 0.55 | 65.6 | 0.55 | 65.6 | 0.80 | 50.0 | 0.65 | 59.4 | 0.70 | 56.3 | 0.40 | 75.0 | 0.70 | 56.3 |
| **Average** | **1.70** | **0.65** | **60.2** | **0.65** | **62.5** | **1.00** | **40.9** | **0.55** | **65.7** | **0.75** | **55.3** | **0.50** | **70.8** | **0.65** | **61.5** |
| **Sample** | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 | 61 |
| **St. Dev.** | **0.19** | **0.20** | **12.51** | **0.17** | **10.51** | **0.18** | **12.28** | **0.19** | **11.59** | **0.20** | **13.42** | **0.20** | **11.99** | **0.22** | **13.31** |
| **Highest** | **2.00** | **1.20** | **84.4** | **1.20** | **86.1** | **1.40** | **65.8** | **1.10** | **88.9** | **1.20** | **80.0** | **1.00** | **92.5** | **1.20** | **85.0** |
| **Lowest** | **1.40** | **0.25** | **21.4** | **0.25** | **33.3** | **0.65** | **12.5** | **0.20** | **31.3** | **0.40** | **21.4** | **0.15** | **42.9** | **0.30** | **32.1** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. **St. Dev.** – Standard Deviation.

**Table H.6:** Turbidity Removal Efficiency of Filters (Run 3)

(Turbidity Unit – NTU)

| Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| **0** | | | | | | | | | | | | | | | |
| **1** | 1.8 | 0.65 | 63.9 | 0.65 | 63.9 | 1.20 | 33.3 | 0.70 | 61.1 | 1.10 | 38.9 | 0.60 | 66.7 | 1.00 | 44.4 |
| **2** | 1.6 | 0.70 | 56.3 | 0.55 | 65.6 | 1.10 | 31.3 | 0.65 | 59.4 | 0.80 | 50.0 | 0.65 | 59.4 | 0.75 | 53.1 |
| **3** | 1.9 | 0.75 | 60.5 | 0.70 | 63.2 | 0.90 | 52.6 | 0.50 | 73.7 | 0.85 | 55.3 | 0.45 | 76.3 | 0.70 | 63.2 |
| **4** | 1.7 | 0.65 | 61.8 | 0.65 | 61.8 | 0.95 | 44.1 | 0.50 | 70.6 | 0.70 | 58.8 | 0.45 | 73.5 | 0.75 | 55.9 |
| **5** | 1.6 | 0.50 | 68.8 | 0.55 | 65.6 | 0.75 | 53.1 | 0.40 | 75.0 | 0.60 | 62.5 | 0.30 | 81.3 | 0.40 | 75.0 |
| **6** | 1.8 | 0.40 | 77.8 | 0.50 | 72.2 | 0.90 | 50.0 | 0.45 | 75.0 | 0.70 | 61.1 | 0.35 | 80.6 | 0.45 | 75.0 |
| **7** | 1.4 | 0.25 | 82.1 | 0.30 | 78.6 | 0.85 | 39.3 | 0.35 | 75.0 | 0.50 | 64.3 | 0.20 | 85.7 | 0.40 | 71.4 |
| **8** | 1.7 | 0.30 | 82.4 | 0.25 | 85.3 | 0.80 | 52.9 | 0.20 | 88.2 | 0.45 | 73.5 | 0.30 | 82.4 | 0.40 | 76.5 |
| **9** | 2 | 0.35 | 82.5 | 0.35 | 82.5 | 0.70 | 65.0 | 0.25 | 87.5 | 0.50 | 75.0 | 0.35 | 82.5 | 0.40 | 80.0 |
| **10** | 1.6 | 0.30 | 81.3 | 0.30 | 81.3 | 0.65 | 59.4 | 0.30 | 81.3 | 0.45 | 71.9 | 0.30 | 81.3 | 0.40 | 75.0 |
| **Average** | **1.70** | **0.50** | **71.7** | **0.50** | **72.0** | **0.90** | **48.1** | **0.45** | **74.7** | **0.65** | **61.1** | **0.40** | **77.0** | **0.55** | **67.0** |
| **Sample** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **St. Dev.** | **0.17** | **0.19** | **10.54** | **0.17** | **9.10** | **0.17** | **10.96** | **0.16** | **9.59** | **0.21** | **11.21** | **0.14** | **8.26** | **0.22** | **12.06** |
| **Highest** | **2.00** | **0.75** | **82.5** | **0.70** | **85.3** | **1.20** | **65.0** | **0.70** | **88.2** | **1.10** | **75.0** | **0.65** | **85.7** | **1.00** | **80.0** |
| **Lowest** | **1.40** | **0.25** | **56.3** | **0.25** | **61.8** | **0.65** | **31.3** | **0.20** | **59.4** | **0.45** | **38.9** | **0.20** | **59.4** | **0.40** | **44.4** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter is 16 hours.
2. **%Rem.** - Percentage removal.
3. **St. Dev.** - Standard deviation.

### *H.3: Feed and Filtrate Water TOC*

**TableH.7:** TOC Removal Efficiencies of Filters (Run 1)

(TOC Unit - mg/L)

| Day | Feed* | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 0 | | | | | | | | | | | | | | | |
| 3 | 0.49 | 0.42 | 14.3 | 0.39 | 20.4 | 0.47 | 4.1 | 0.42 | 14.3 | 0.44 | 10.2 | 0.40 | 18.4 | 0.45 | 8.2 |
| 6 | 0.37 | 0.32 | 13.5 | 0.34 | 8.1 | 0.35 | 5.4 | 0.31 | 16.2 | 0.33 | 10.8 | 0.29 | 21.6 | 0.33 | 10.8 |
| 7 | 0.46 | 0.37 | 19.6 | 0.38 | 17.4 | 0.41 | 10.9 | 0.33 | 28.3 | 0.40 | 13.0 | 0.34 | 26.1 | 0.43 | 6.5 |
| 9 | 0.26 | 0.18 | 30.8 | 0.19 | 26.9 | 0.25 | 3.8 | 0.17 | 34.6 | 0.22 | 15.4 | 0.15 | 42.3 | 0.20 | 23.1 |
| 10 | 0.45 | 0.35 | 22.2 | 0.34 | 24.4 | 0.38 | 15.6 | 0.33 | 26.7 | 0.37 | 17.8 | 0.33 | 26.7 | 0.36 | 20.0 |
| 12 | 0.41 | 0.16 | 61.0 | 0.14 | 65.9 | 0.27 | 34.1 | 0.14 | 65.9 | 0.23 | 43.9 | 0.12 | 70.7 | 0.19 | 53.7 |
| 13 | 0.24 | 0.10 | 57.5 | 0.08 | 66.0 | 0.14 | 40.5 | 0.09 | 61.7 | 0.13 | 44.7 | 0.08 | 66.0 | 0.14 | 40.5 |
| 15 | 0.31 | 0.14 | 54.8 | 0.14 | 54.8 | 0.19 | 38.7 | 0.13 | 58.1 | 0.21 | 32.3 | 0.15 | 51.6 | 0.19 | 38.7 |
| 18 | 0.26 | 0.09 | 65.4 | 0.09 | 65.4 | 0.14 | 46.2 | 0.08 | 69.2 | 0.13 | 50.0 | 0.08 | 69.2 | 0.11 | 57.7 |
| 19 | 0.23 | 0.07 | 69.6 | 0.08 | 65.2 | 0.11 | 52.2 | 0.07 | 69.6 | 0.10 | 56.5 | 0.06 | 73.9 | 0.10 | 56.5 |
| **Average** | **0.35** | **0.22** | **40.9** | **0.22** | **41.5** | **0.27** | **25.1** | **0.21** | **44.4** | **0.26** | **29.5** | **0.20** | **46.7** | **0.25** | **31.6** |
| **Sample** | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| **St. Dev.** | **0.10** | **0.13** | **22.75** | **0.13** | **23.92** | **0.13** | **19.02** | **0.13** | **22.53** | **0.12** | **18.03** | **0.13** | **22.36** | **0.13** | **20.37** |
| **Highest** | **0.49** | **0.42** | **69.6** | **0.39** | **66.0** | **0.47** | **52.2** | **0.42** | **69.6** | **0.44** | **56.5** | **0.40** | **73.9** | **0.45** | **57.7** |
| **Lowest** | **0.23** | **0.07** | **13.5** | **0.08** | **8.1** | **0.11** | **3.8** | **0.07** | **14.3** | **0.10** | **10.2** | **0.06** | **18.4** | **0.10** | **6.5** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. **St. Dev.** - Standard deviation.

**Table H.8:** TOC Removal Efficiencies of Filters (Run 2)
(TOC Unit – mg/L)

| Day | Feed* | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| **0** | | | | | | | | | | | | | | | |
| **23** | 9.03 | 3.42 | 62.1 | 3.50 | 61.2 | 4.62 | 48.8 | 3.54 | 60.8 | 4.63 | 48.7 | 3.32 | 63.2 | 4.61 | 48.9 |
| **24** | 8.53 | 3.21 | 62.4 | 3.32 | 61.1 | 4.52 | 47.0 | 3.30 | 61.3 | 4.58 | 46.3 | 3.21 | 62.4 | 4.42 | 48.2 |
| **25** | 8.12 | 3.14 | 61.3 | 3.10 | 61.8 | 4.55 | 44.0 | 3.05 | 62.4 | 4.51 | 44.5 | 3.10 | 61.8 | 4.40 | 45.8 |
| **26** | 8.12 | 3.10 | 61.8 | 3.10 | 61.8 | 4.36 | 46.3 | 3.20 | 60.6 | 4.40 | 45.8 | 3.15 | 61.2 | 4.42 | 45.6 |
| **27** | 6.75 | 2.50 | 63.0 | 2.60 | 61.5 | 3.41 | 49.5 | 2.58 | 61.8 | 3.21 | 52.4 | 2.51 | 62.8 | 3.20 | 52.6 |
| **31** | 4.53 | 1.51 | 66.7 | 1.45 | 68.0 | 2.73 | 39.7 | 1.40 | 69.1 | 2.45 | 45.9 | 1.36 | 70.0 | 2.42 | 46.6 |
| **32** | 4.68 | 1.46 | 68.8 | 1.40 | 70.1 | 2.68 | 42.7 | 1.32 | 71.8 | 2.31 | 50.6 | 1.35 | 71.2 | 2.40 | 48.7 |
| **33** | 4.57 | 1.60 | 65.0 | 1.58 | 65.4 | 2.78 | 39.2 | 1.40 | 69.4 | 2.25 | 50.8 | 1.41 | 69.1 | 2.19 | 52.1 |
| **36** | 4.62 | 1.26 | 72.7 | 1.08 | 76.6 | 2.54 | 45.0 | 1.20 | 74.0 | 2.31 | 50.0 | 1.08 | 76.6 | 2.11 | 54.3 |
| **37** | 5.21 | 0.90 | 82.7 | 0.88 | 83.1 | 1.95 | 62.6 | 0.86 | 83.5 | 1.46 | 72.0 | 0.78 | 85.0 | 1.40 | 73.1 |
| **38** | 4.92 | 0.74 | 85.0 | 0.70 | 85.8 | 1.88 | 61.8 | 0.71 | 85.6 | 1.31 | 73.4 | 0.74 | 85.0 | 1.11 | 77.4 |
| **39** | 4.62 | 0.62 | 86.6 | 0.60 | 87.0 | 1.90 | 58.9 | 0.56 | 87.9 | 1.10 | 76.2 | 0.76 | 83.5 | 0.94 | 79.7 |
| **42** | 7.51 | 1.32 | 82.4 | 0.80 | 89.3 | 1.60 | 78.7 | 0.75 | 90.0 | 1.15 | 84.7 | 0.81 | 89.2 | 0.82 | 89.1 |
| **43** | 7.91 | 1.24 | 84.3 | 0.76 | 90.4 | 1.58 | 80.0 | 0.68 | 91.4 | 0.98 | 87.6 | 0.72 | 90.9 | 0.85 | 89.3 |
| **46** | 7.69 | 0.89 | 88.4 | 0.90 | 88.3 | 1.35 | 82.4 | 0.63 | 91.8 | 0.87 | 88.7 | 0.81 | 89.5 | 0.78 | 89.9 |
| **47** | 7.12 | 0.99 | 86.1 | 1.14 | 84.0 | 1.42 | 80.1 | 0.70 | 90.2 | 0.85 | 88.1 | 0.93 | 86.9 | 0.90 | 87.4 |
| **48** | 6.89 | 0.88 | 87.2 | 0.87 | 87.4 | 1.52 | 77.9 | 0.71 | 89.7 | 0.92 | 86.6 | 0.87 | 87.4 | 0.93 | 86.5 |
| **52** | 8.12 | 1.05 | 87.1 | 1.18 | 85.5 | 1.40 | 82.8 | 1.10 | 86.5 | 0.93 | 88.5 | 0.92 | 88.7 | 0.98 | 87.9 |
| **53** | 7.48 | 0.97 | 87.0 | 0.93 | 87.6 | 1.36 | 81.8 | 0.82 | 89.0 | 1.1 | 85.3 | 0.78 | 89.6 | 0.85 | 88.6 |
| **55** | 7.69 | 0.87 | 88.7 | 0.86 | 88.8 | 1.26 | 83.6 | 0.69 | 91.0 | 0.91 | 88.2 | 0.73 | 90.5 | 0.82 | 89.3 |
| **56** | 7.42 | 0.92 | 87.6 | 0.88 | 88.1 | 1.21 | 83.7 | 0.87 | 88.3 | 0.87 | 88.3 | 0.62 | 91.6 | 0.71 | 90.4 |
| **57** | 7.35 | 0.51 | 93.1 | 0.60 | 91.8 | 1.22 | 83.4 | 0.49 | 93.3 | 0.89 | 87.9 | 0.55 | 92.5 | 0.76 | 89.7 |
| **59** | 7.91 | 0.61 | 92.3 | 0.52 | 93.4 | 1.25 | 84.2 | 0.55 | 93.0 | 0.93 | 88.2 | 0.53 | 93.3 | 0.87 | 89.0 |
| **60** | 7.68 | 0.64 | 91.7 | 0.57 | 92.6 | 1.21 | 84.2 | 0.55 | 92.8 | 1.10 | 85.7 | 0.59 | 92.3 | 0.88 | 88.5 |
| **Average** | **6.85** | **1.43** | **78.9** | **1.39** | **79.6** | **2.26** | **65.3** | **1.32** | **80.6** | **1.92** | **71.0** | **1.32** | **80.6** | **1.82** | **72.4** |
| **Sample** | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 | 24 |
| **St. Dev.** | **1.47** | **0.92** | **11.62** | **0.96** | **12.00** | **1.19** | **17.88** | **1.00** | **12.44** | **1.35** | **18.57** | **0.95** | **11.85** | **1.38** | **18.93** |
| **Highest** | **9.03** | **3.42** | **93.1** | **3.50** | **93.4** | **4.62** | **84.2** | **3.54** | **93.3** | **4.63** | **88.7** | **3.32** | **93.3** | **4.61** | **90.4** |
| **Lowest** | **4.53** | **0.51** | **61.3** | **0.52** | **61.1** | **1.21** | **39.2** | **0.49** | **60.6** | **0.85** | **44.5** | **0.53** | **61.2** | **0.71** | **45.6** |

**Table H.9:** TOC Removal Efficiency of Filters (Run 3)
(TOC Unit - mg/L)

| Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 0 | | | | | | | | | | | | | | | |
| 1 | 4.68 | 1.94 | 58.5 | 1.88 | 59.8 | 2.32 | 50.4 | 1.51 | 67.7 | 1.73 | 63.0 | 1.45 | 69.0 | 1.52 | 67.5 |
| 2 | 4.82 | 1.31 | 72.8 | 1.22 | 74.7 | 1.56 | 67.6 | 0.78 | 83.8 | 0.94 | 80.5 | 0.74 | 84.6 | 0.84 | 82.6 |
| 3 | 6.89 | 1.10 | 84.0 | 0.95 | 86.2 | 1.68 | 75.6 | 0.63 | 90.9 | 0.84 | 87.8 | 0.52 | 92.5 | 0.71 | 89.7 |
| 5 | 7.21 | 0.82 | 88.6 | 0.75 | 89.6 | 1.12 | 84.5 | 0.65 | 91.0 | 0.85 | 88.2 | 0.55 | 92.4 | 1.05 | 85.4 |
| 7 | 7.59 | 0.61 | 92.0 | 0.67 | 91.2 | 1.21 | 84.1 | 0.65 | 91.4 | 1.17 | 84.6 | 0.46 | 93.9 | 0.96 | 87.4 |
| 8 | 8.12 | 0.54 | 93.3 | 0.61 | 92.5 | 1.08 | 86.7 | 0.64 | 92.1 | 1.21 | 85.1 | 0.57 | 93.0 | 0.85 | 89.5 |
| 9 | 7.06 | 0.55 | 92.2 | 0.61 | 91.4 | 1.32 | 81.3 | 0.52 | 92.6 | 1.23 | 82.6 | 0.48 | 93.2 | 0.89 | 87.4 |
| **Average** | **6.95** | **0.82** | **87.2** | **0.80** | **87.6** | **1.33** | **80.0** | **0.65** | **90.3** | **1.04** | **84.8** | **0.55** | **91.6** | **0.88** | **87.0** |
| **Sample** | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| **St. Dev.** | **1.13** | **0.32** | **7.80** | **0.24** | **6.68** | **0.24** | **7.14** | **0.08** | **3.25** | **0.18** | **2.98** | **0.10** | **3.45** | **0.12** | **2.68** |
| **Highest** | **8.12** | **1.31** | **93.3** | **1.22** | **92.5** | **1.68** | **86.7** | **0.78** | **92.6** | **1.23** | **88.2** | **0.74** | **93.9** | **1.05** | **89.7** |
| **Lowest** | **4.82** | **0.54** | **72.8** | **0.61** | **74.7** | **1.08** | **67.6** | **0.52** | **83.8** | **0.84** | **80.5** | **0.46** | **84.6** | **0.71** | **82.6** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. **St. Dev.** - Standard deviation.

*H.4: Ammonia-Nitrogen Removal*

**Table H.10:** Ammonia-Nitrogen Removal Efficiencies During Run 2
(Ammonia-Nitrogen Concentration - mg/L)

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Faric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 5-Mar | 1 | 0.75 | 0.55 | 26.7 | 0.59 | 21.3 | 0.67 | 10.7 | 0.60 | 20.0 | 0.67 | 10.7 | 0.61 | 18.7 | 0.63 | 16.0 |
| 6-Mar | 2 | 0.66 | 0.50 | 24.2 | 0.49 | 25.8 | 0.56 | 15.2 | 0.50 | 24.2 | 0.54 | 18.2 | 0.48 | 27.3 | 0.55 | 16.7 |
| 7-Mar | 3 | 0.64 | 0.42 | 34.4 | 0.51 | 20.3 | 0.56 | 12.5 | 0.48 | 25.0 | 0.52 | 18.8 | 0.52 | 18.8 | 0.50 | 21.9 |
| 9-Mar | 5 | 0.9 | 0.64 | 28.9 | 0.55 | 38.9 | 0.75 | 16.7 | 0.52 | 42.2 | 0.74 | 17.8 | 0.56 | 37.8 | 0.68 | 24.4 |
| 10-Mar | 6 | 0.77 | 0.54 | 29.9 | 0.53 | 31.2 | 0.65 | 15.6 | 0.54 | 29.9 | 0.66 | 14.3 | 0.51 | 33.8 | 0.64 | 16.9 |
| 13-Mar | 9 | 0.61 | 0.41 | 32.8 | 0.38 | 37.7 | 0.52 | 14.8 | 0.34 | 44.3 | 0.52 | 14.8 | 0.45 | 26.2 | 0.42 | 31.1 |
| 14-Mar | 10 | 0.58 | 0.48 | 17.2 | 0.27 | 53.4 | 0.48 | 17.2 | 0.26 | 55.2 | 0.46 | 20.7 | 0.31 | 46.6 | 0.38 | 34.5 |
| 17-Mar | 13 | 0.67 | 0.36 | 46.3 | 0.35 | 47.8 | 0.54 | 19.4 | 0.35 | 47.8 | 0.51 | 23.9 | 0.32 | 52.2 | 0.45 | 32.8 |
| 18-Mar | 14 | 0.88 | 0.52 | 40.9 | 0.45 | 48.9 | 0.72 | 18.2 | 0.48 | 45.5 | 0.67 | 23.9 | 0.37 | 58.0 | 0.60 | 31.8 |
| 19-Mar | 15 | 0.75 | 0.43 | 42.7 | 0.46 | 38.7 | 0.61 | 18.7 | 0.50 | 33.3 | 0.51 | 32.0 | 0.41 | 45.3 | 0.49 | 34.7 |
| 23-Mar | 19 | 0.85 | 0.65 | 23.5 | 0.51 | 40.0 | 0.75 | 11.8 | 0.42 | 50.6 | 0.68 | 20.0 | 0.47 | 44.7 | 0.64 | 24.7 |
| 24-Mar | 20 | 0.62 | 0.36 | 41.9 | 0.41 | 33.9 | 0.50 | 19.4 | 0.38 | 38.7 | 0.45 | 27.4 | 0.42 | 32.3 | 0.46 | 25.8 |
| 27-Mar | 23 | 0.68 | 0.31 | 54.4 | 0.42 | 38.2 | 0.57 | 16.2 | 0.36 | 47.1 | 0.51 | 25.0 | 0.38 | 44.1 | 0.43 | 36.8 |
| 28-Mar | 24 | 0.51 | 0.34 | 33.3 | 0.34 | 33.3 | 0.42 | 17.6 | 0.31 | 39.2 | 0.41 | 19.6 | 0.28 | 45.1 | 0.31 | 39.2 |
| 30-Mar | 26 | 0.47 | 0.24 | 48.9 | 0.35 | 25.5 | 0.37 | 21.3 | 0.29 | 38.3 | 0.38 | 19.1 | 0.27 | 42.6 | 0.31 | 34.0 |
| 31-Mar | 27 | 0.38 | 0.19 | 50.0 | 0.21 | 44.7 | 0.31 | 18.4 | 0.16 | 57.9 | 0.24 | 36.8 | 0.19 | 50.0 | 0.22 | 42.1 |
| 4-Apr | 31 | 0.65 | 0.30 | 53.8 | 0.41 | 36.9 | 0.51 | 21.5 | 0.42 | 35.4 | 0.41 | 36.9 | 0.39 | 40.0 | 0.37 | 43.1 |
| 5-Apr | 32 | 0.61 | 0.31 | 49.2 | 0.41 | 32.8 | 0.45 | 26.2 | 0.37 | 39.3 | 0.42 | 31.1 | 0.37 | 39.3 | 0.38 | 37.7 |
| 6-Apr | 33 | 0.34 | 0.15 | 55.9 | 0.19 | 44.1 | 0.24 | 29.4 | 0.15 | 55.9 | 0.16 | 52.9 | 0.17 | 50.0 | 0.18 | 47.1 |
| 10-Apr | 37 | 0.34 | 0.12 | 64.7 | 0.07 | 79.4 | 0.18 | 47.1 | 0.08 | 76.5 | 0.09 | 73.5 | 0.08 | 76.5 | 0.11 | 67.6 |
| 11-Apr | 38 | 0.44 | 0.08 | 81.8 | 0.06 | 86.4 | 0.20 | 54.5 | 0.05 | 88.6 | 0.10 | 77.3 | 0.07 | 84.1 | 0.09 | 79.5 |
| 12-Apr | 39 | 0.27 | 0.06 | 78.1 | 0.05 | 81.8 | 0.12 | 56.3 | 0.05 | 81.8 | 0.07 | 74.5 | 0.05 | 81.8 | 0.07 | 74.5 |
| 15-Apr | 42 | 0.45 | 0.16 | 64.4 | 0.14 | 68.9 | 0.16 | 64.4 | 0.10 | 77.8 | 0.11 | 75.6 | 0.11 | 75.6 | 0.12 | 73.3 |
| 16-Apr | 43 | 0.64 | 0.20 | 68.8 | 0.26 | 59.4 | 0.28 | 56.3 | 0.21 | 67.2 | 0.23 | 64.1 | 0.19 | 70.3 | 0.20 | 68.8 |
| 17-Apr | 44 | 0.65 | 0.24 | 63.1 | 0.35 | 46.2 | 0.36 | 44.6 | 0.31 | 52.3 | 0.36 | 44.6 | 0.21 | 67.7 | 0.23 | 64.6 |
| 20-Apr | 47 | 0.55 | 0.21 | 61.8 | 0.15 | 72.7 | 0.21 | 61.8 | 0.12 | 78.2 | 0.15 | 72.7 | 0.14 | 74.5 | 0.15 | 72.7 |
| 21-Apr | 48 | 0.61 | 0.16 | 73.8 | 0.11 | 82.0 | 0.19 | 68.9 | 0.11 | 82.0 | 0.18 | 70.5 | 0.09 | 85.2 | 0.12 | 80.3 |
| 23-Apr | 50 | 0.63 | 0.12 | 81.0 | 0.19 | 69.8 | 0.26 | 59.0 | 0.14 | 77.8 | 0.15 | 76.2 | 0.16 | 74.6 | 0.18 | 71.4 |
| 24-Apr | 51 | 0.65 | 0.11 | 83.1 | 0.18 | 72.3 | 0.21 | 67.7 | 0.19 | 70.8 | 0.20 | 69.2 | 0.16 | 75.4 | 0.17 | 73.8 |
| 25-Apr | 52 | 0.45 | 0.09 | 80.0 | 0.05 | 88.9 | 0.12 | 73.3 | 0.05 | 88.9 | 0.11 | 75.6 | 0.05 | 88.9 | 0.07 | 84.4 |

**Table H.10:** Continued

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 29-Apr | **56** | 0.35 | 0.05 | 85.7 | 0.05 | 85.7 | 0.07 | 80.0 | 0.06 | 82.9 | 0.09 | 74.3 | 0.05 | 85.7 | 0.06 | 82.9 |
| 30-Apr | **57** | 0.51 | 0.12 | 76.5 | 0.15 | 70.6 | 0.18 | 64.7 | 0.12 | 76.5 | 0.15 | 70.6 | 0.10 | 80.4 | 0.11 | 78.4 |
| 1-May | **58** | 0.34 | 0.05 | 85.3 | 0.05 | 85.3 | 0.07 | 79.4 | 0.05 | 85.3 | 0.10 | 70.6 | 0.05 | 85.3 | 0.06 | 82.4 |
| 3-May | **60** | 0.33 | 0.06 | 81.8 | 0.05 | 84.8 | 0.07 | 78.8 | 0.06 | 81.8 | 0.09 | 72.7 | 0.08 | 75.8 | 0.09 | 72.7 |
| 4-May | **61** | 0.35 | 0.07 | 80.0 | 0.05 | 85.7 | 0.08 | 77.1 | 0.07 | 80.0 | 0.06 | 82.9 | 0.05 | 85.7 | 0.06 | 82.9 |
| **Average** | | **0.57** | **0.27** | **55.6** | **0.28** | **54.7** | **0.37** | **39.3** | **0.26** | **57.7** | **0.33** | **46.0** | **0.26** | **57.7** | **0.30** | **51.5** |
| **Sample** | | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| **St. Dev.** | | **0.17** | **0.18** | **21.28** | **0.18** | **22.52** | **0.22** | **24.98** | **0.17** | **21.37** | **0.22** | **25.52** | **0.17** | **21.95** | **0.20** | **23.83** |
| **Highest** | | **0.90** | **0.65** | **85.7** | **0.59** | **88.9** | **0.75** | **80.0** | **0.60** | **88.9** | **0.74** | **82.9** | **0.61** | **88.9** | **0.68** | **84.4** |
| **Lowest** | | **0.27** | **0.05** | **17.2** | **0.05** | **20.3** | **0.07** | **10.7** | **0.05** | **20.0** | **0.06** | **10.7** | **0.05** | **18.7** | **0.06** | **16.0** |

**Table H.11:** Ammonia-Nitrogen Removal Efficiencies During Run 3
(Ammonia-Nitrogen Concentration - mg/L)

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 6-May | **0** | | | | | | | | | | | | | | | |
| 8-May | **2** | 0.39 | 0.18 | 53.7 | 0.14 | 64.0 | 0.22 | 43.4 | 0.15 | 61.4 | 0.24 | 38.3 | 0.11 | 71.7 | 0.21 | 46.0 |
| 9-May | **3** | 0.28 | 0.04 | 85.9 | 0.04 | 85.8 | 0.18 | 38.5 | 0.05 | 83.4 | 0.18 | 37.5 | 0.04 | 85.3 | 0.26 | 7.8 |
| 10-May | **4** | 0.39 | 0.20 | 48.1 | 0.05 | 86.9 | 0.04 | 89.2 | 0.05 | 87.7 | 0.05 | 88.3 | 0.04 | 89.2 | 0.07 | 82.2 |
| 12-May | **6** | 0.35 | 0.21 | 39.5 | 0.08 | 76.9 | 0.11 | 68.3 | 0.06 | 82.7 | 0.14 | 59.7 | 0.06 | 82.7 | 0.09 | 74.1 |
| 15-May | **9** | 0.46 | 0.22 | 52.4 | 0.21 | 54.6 | 0.35 | 24.3 | 0.18 | 61.1 | 0.41 | 11.4 | 0.22 | 52.4 | 0.34 | 26.5 |
| 16-May | **10** | 0.31 | 0.21 | 33.3 | 0.18 | 42.8 | 0.27 | 14.3 | 0.16 | 49.2 | 0.12 | 61.9 | 0.19 | 39.7 | 0.26 | 17.4 |
| **Average** | | **0.36** | **0.18** | **52.2** | **0.12** | **68.5** | **0.19** | **46.3** | **0.11** | **70.9** | **0.19** | **49.5** | **0.11** | **70.2** | **0.21** | **42.3** |
| **Sample** | | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| **St. Dev.** | | **0.06** | **0.07** | **18.31** | **0.07** | **17.80** | **0.11** | **27.95** | **0.06** | **15.72** | **0.13** | **26.41** | **0.08** | **19.99** | **0.11** | **30.58** |
| **Highest** | | **0.46** | **0.22** | **85.9** | **0.21** | **86.9** | **0.35** | **89.2** | **0.18** | **87.7** | **0.41** | **88.3** | **0.22** | **89.2** | **0.34** | **82.2** |
| **Lowest** | | **0.28** | **0.04** | **33.3** | **0.04** | **42.8** | **0.04** | **14.3** | **0.05** | **49.2** | **0.05** | **11.4** | **0.04** | **39.7** | **0.07** | **7.8** |

1. Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. **St.Dev.**-Standard Deviation.

### *H.5: Nitrate-Nitrogen in Feed and Filtrates*

**Table H.12:** Nitrate-Nitrogen in Feed and Filtrates During Run 2

(Nitrate-Nitrogen Concentration - mg/L)

| Date | Day | Feed (16h) | Filter 1 | Filter 2 | | Filter 3 | | Filter 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Total | Total | Fabric | Total | Fabric | Total | Fabric |
| 4-Mar | **0** | | | | | | | | |
| 5-Mar | **1** | 0.95 | 0.85 | 0.87 | 0.89 | 0.90 | 0.91 | 0.91 | 0.92 |
| 6-Mar | **2** | 1.22 | 1.10 | 1.20 | 1.20 | 1.10 | 1.12 | 1.12 | 1.16 |
| 7-Mar | **3** | 1.4 | 0.95 | 1.10 | 1.13 | 0.93 | 1.21 | 1.10 | 1.24 |
| 9-Mar | **5** | 1.54 | 0.97 | 0.96 | 1.21 | 0.85 | 1.30 | 0.98 | 1.21 |
| 10-Mar | **6** | 2.1 | 1.10 | 1.20 | 1.65 | 1.15 | 1.65 | 1.21 | 1.36 |
| 13-Mar | **9** | 1.65 | 0.68 | 0.78 | 1.52 | 0.71 | 1.32 | 0.85 | 1.10 |
| 14-Mar | **10** | 1.85 | 0.78 | 0.85 | 1.65 | 0.73 | 1.21 | 0.85 | 1.17 |
| 17-Mar | **13** | 1.98 | 0.89 | 0.88 | 1.70 | 0.93 | 1.35 | 0.92 | 0.95 |
| 18-Mar | **14** | 1.21 | 0.65 | 0.69 | 1.10 | 0.64 | 0.95 | 0.61 | 0.85 |
| 19-Mar | **15** | 1.52 | 0.64 | 0.53 | 1.12 | 0.67 | 1.15 | 0.60 | 0.90 |
| 23-Mar | **19** | 1.75 | 0.66 | 0.68 | 1.21 | 0.62 | 1.22 | 0.62 | 1.23 |
| 24-Mar | **20** | 1.73 | 0.57 | 0.58 | 1.06 | 0.53 | 0.95 | 0.59 | 1.11 |
| 27-Mar | **23** | 1.65 | 0.84 | 0.85 | 0.90 | 0.91 | 1.10 | 0.78 | 1.15 |
| 28-Mar | **24** | 1.45 | 0.81 | 0.75 | 0.95 | 0.75 | 0.75 | 0.83 | 0.95 |
| 30-Mar | **26** | 1.08 | 0.64 | 0.63 | 0.75 | 0.61 | 0.75 | 0.72 | 0.88 |
| 31-Mar | **27** | 1.85 | 0.58 | 0.66 | 0.73 | 0.55 | 0.66 | 0.68 | 0.97 |
| 4-Apr | **31** | 1.24 | 0.54 | 0.68 | 0.85 | 0.64 | 0.71 | 0.56 | 0.77 |
| 5-Apr | **32** | 0.96 | 0.45 | 0.58 | 0.64 | 0.50 | 0.63 | 0.42 | 0.68 |
| 6-Apr | **33** | 1.34 | 0.42 | 0.46 | 0.52 | 0.40 | 0.54 | 0.41 | 0.66 |
| 10-Apr | **37** | 1.36 | 0.36 | 0.34 | 0.45 | 0.30 | 0.35 | 0.30 | 0.50 |
| 11-Apr | **38** | 1.80 | 0.37 | 0.34 | 0.44 | 0.25 | 0.27 | 0.32 | 0.34 |
| 12-Apr | **39** | 2.10 | 0.41 | 0.36 | 0.49 | 0.42 | 0.46 | 0.34 | 0.37 |
| 15-Apr | **42** | 1.60 | 0.46 | 0.41 | 0.46 | 0.47 | 0.51 | 0.48 | 0.54 |
| 16-Apr | **43** | 1.54 | 0.37 | 0.30 | 0.35 | 0.34 | 0.43 | 0.36 | 0.44 |
| 17-Apr | **44** | 2.10 | 0.39 | 0.25 | 0.28 | 0.28 | 0.34 | 0.31 | 0.45 |
| 20-Apr | **47** | 1.40 | 0.34 | 0.24 | 0.29 | 0.21 | 0.26 | 0.31 | 0.38 |
| 21-Apr | **48** | 1.32 | 0.20 | 0.25 | 0.29 | 0.23 | 0.28 | 0.15 | 0.24 |
| 23-Apr | **50** | 2.10 | 0.40 | 0.31 | 0.37 | 0.34 | 0.41 | 0.25 | 0.33 |

**Table H.12:** Continued

| Date | Day | Feed | Filter 1 | Filter 2 | | Filter 3 | | Filter 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | Total | Fabric | Total | Fabric | Total | Fabric |
| 24-Apr | **51** | 1.54 | 0.52 | 0.41 | 0.46 | 0.45 | 0.47 | 0.45 | 0.49 |
| 25-Apr | **52** | 1.50 | 0.35 | 0.36 | 0.37 | 0.36 | 0.41 | 0.31 | 0.39 |
| 29-Apr | **56** | 1.12 | 0.25 | 0.20 | 0.24 | 0.24 | 0.33 | 0.35 | 0.42 |
| 30-Apr | **57** | 1.54 | 0.24 | 0.21 | 0.26 | 0.21 | 0.34 | 0.23 | 0.32 |
| 1-May | **58** | 1.36 | 0.20 | 0.22 | 0.27 | 0.24 | 0.29 | 0.21 | 0.29 |
| 3-May | **60** | 1.25 | 0.23 | 0.31 | 0.34 | 0.26 | 0.27 | 0.15 | 0.21 |
| 4-May | **61** | 1.60 | 0.36 | 0.21 | 0.29 | 0.31 | 0.42 | 0.21 | 0.25 |
| **Average** | | **1.53** | **0.56** | **0.56** | **0.76** | **0.54** | **0.72** | **0.56** | **0.72** |
| **Sample** | | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 35 |
| **St. Dev.** | | **0.32** | **0.26** | **0.30** | **0.45** | **0.27** | **0.40** | **0.30** | **0.36** |
| **Highest** | | **2.10** | **1.10** | **1.20** | **1.70** | **1.15** | **1.65** | **1.21** | **1.36** |
| **Lowest** | | **0.95** | **0.20** | **0.20** | **0.24** | **0.21** | **0.26** | **0.15** | **0.21** |

**Table H.13:** Nitrate-Nitrogen in Feed and Filtrates During Run 3

(Nitrate-Nitrogen Concentration - mg/L)

| Date | Day | Feed | Filter 1 | Filter 2 | | Filter 3 | | Filter 4 | |
|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | Total | Fabric | Total | Fabric | Total | Fabric |
| 6-May | **0** | | | | | | | | |
| 8-May | **2** | 0.37 | 0.34 | 0.33 | 0.36 | 0.31 | 0.33 | 0.34 | 0.33 |
| 9-May | **3** | 0.67 | 0.64 | 0.61 | 0.56 | 0.65 | 0.58 | 0.62 | 0.53 |
| 10-May | **4** | 0.45 | 0.31 | 0.32 | 0.16 | 0.17 | 0.15 | 0.07 | 0.10 |
| 12-May | **6** | 0.65 | 0.30 | 0.18 | 0.18 | 0.19 | 0.12 | 0.10 | 0.10 |
| 15-May | **9** | 0.64 | 0.23 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| 16-May | **10** | 0.43 | 0.19 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| **Average** | | **0.54** | **0.34** | **0.27** | **0.24** | **0.25** | **0.23** | **0.22** | **0.21** |
| **Sample** | | **6** | **6** | **6** | **6** | **6** | **6** | **6** | **6** |
| **St. Dev.** | | **0.13** | **0.16** | **0.19** | **0.18** | **0.21** | **0.19** | **0.22** | **0.18** |
| **Highest** | | **0.67** | **0.64** | **0.61** | **0.56** | **0.65** | **0.58** | **0.62** | **0.53** |
| **Lowest** | | **0.37** | **0.19** | **0.10** | **0.10** | **0.10** | **0.10** | **0.07** | **0.00** |

### *H.6: Feed and Filtrate Coliform and Removal Efficiencies*

**Table H.14:** Total Coliform Removal Efficiencies of Filters (Run 2)
(Coliform Unit – CFU/100 mL)

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 10-Apr | 37 | 3670 | 5 | 99.86 | 1 | 99.97 | 986 | 73.13 | 1 | 99.97 | 1108 | 69.81 | 12 | 99.67 | 1354 | 63.11 |
| 11-Apr | 38 | 3750 | <1 | 100.00 | 1 | 99.97 | 1432 | 61.81 | <1 | 100.00 | 1350 | 64.00 | <1 | 100.00 | 978 | 73.92 |
| 12-Apr | 39 | 5430 | 15 | 99.72 | 20 | 99.63 | 1558 | 71.31 | 12 | 99.78 | 2140 | 60.59 | 10 | 99.82 | 1875 | 65.47 |
| 16-Apr | 43 | 3880 | 34 | 99.12 | 18 | 99.54 | 1645 | 57.60 | 21 | 99.46 | 1255 | 67.65 | 17 | 99.56 | 1425 | 63.27 |
| 17-Apr | 44 | 3520 | 10 | 99.72 | 36 | 98.98 | 1568 | 55.45 | 41 | 98.84 | 1265 | 64.06 | 37 | 98.95 | 1182 | 66.42 |
| 21-Apr | 48 | 5890 | 14 | 99.76 | 11 | 99.81 | 1876 | 68.15 | 19 | 99.68 | 2132 | 63.80 | 10 | 99.83 | 1680 | 71.48 |
| 22-Apr | 49 | 4780 | 27 | 99.44 | 36 | 99.25 | 2120 | 55.65 | 21 | 99.56 | 1245 | 73.95 | 35 | 99.27 | 1398 | 70.75 |
| 24-Apr | 51 | 9430 | 38 | 99.60 | 85 | 99.10 | 2820 | 70.10 | 41 | 99.57 | 2688 | 71.50 | 21 | 99.78 | 2770 | 70.63 |
| 26-Apr | 53 | 6860 | <1 | 100.00 | <1 | 100.00 | 1421 | 79.29 | <1 | 100.00 | 2430 | 64.58 | <1 | 100.00 | 1878 | 72.62 |
| 29-Apr | 56 | 6590 | 56 | 99.15 | 24 | 99.64 | 1980 | 69.95 | 14 | 99.79 | 1665 | 74.73 | <1 | 100.00 | 1546 | 76.54 |
| 30-Apr | 57 | 10930 | 24 | 99.78 | 2 | 99.98 | 3100 | 71.64 | 24 | 99.78 | 3150 | 71.18 | 10 | 99.91 | 3144 | 71.24 |
| **Average** | | **5885** | **20** | **99.65** | **21.27** | **99.62** | **1864** | **66.73** | **18** | **99.67** | **1857** | **67.81** | **14** | **99.71** | **1748** | **69.59** |
| **Sample** | | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11.00 |
| **St. Dev.** | | **2449** | **17** | **0.30** | **25** | **0.37** | **625** | **7.90** | **14** | **0.33** | **692** | **4.71** | **13** | **0.33** | **661** | **4.40** |
| **Highest** | | **10930** | **56** | **100.00** | **85** | **100.00** | **3100** | **79.29** | **41** | **100.00** | **3150** | **74.73** | **37** | **100.00** | **3144** | **76.54** |
| **Lowest** | | **3520** | <1 | **99.12** | <1 | **98.98** | **986** | **55.45** | <1 | **98.84** | **1108** | **60.59** | <1 | **98.95** | **978** | **63.11** |

1. * Feed measurements were taken 16 hours before the filtrate measurements; Residence time for the filter was 16 hours.
2. **%Rem.** - Percentage removal.
3. St. Dev. – Standard Deviation.

**Table H.15:** *E. coli* Removal Efficiencies of Filters (Run 2)

(*E. coli* Unit – CFU/100 mL)

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 10-Apr | **37** | 280 | <1 | 100.00 | 1 | 99.64 | 18 | 93.57 | 2 | 99.29 | 37 | 86.79 | <1 | 100.00 | 42 | 85.0 |
| 11-Apr | **38** | 160 | <1 | 100.00 | <1 | 100.00 | <1 | 100.00 | <1 | 100.00 | <1 | 100.00 | <1 | 100.00 | 1 | 99.4 |
| 12-Apr | **39** | 470 | <1 | 100.00 | 3 | 99.36 | 35 | 92.55 | 1 | 99.79 | 42 | 91.06 | <1 | 100.00 | 36 | 92.3 |
| 16-Apr | **43** | 170 | <1 | 100.00 | 2 | 98.82 | 20 | 88.24 | <1 | 100.00 | 34 | 80.00 | 1 | 99.41 | 28 | 83.5 |
| 17-Apr | **44** | 220 | 1 | 99.55 | <1 | 100.00 | 24 | 89.09 | <1 | 100.00 | 14 | 93.64 | 2 | 99.09 | 44 | 80.0 |
| 21-Apr | **48** | 420 | 2 | 99.52 | <1 | 100.00 | 62 | 85.24 | 2 | 99.52 | 52 | 87.62 | <1 | 100.00 | 36 | 91.4 |
| 22-Apr | **49** | 590 | 3 | 99.49 | 2 | 99.66 | 58 | 90.17 | 3 | 99.49 | 42 | 92.88 | 1 | 99.83 | 10 | 98.3 |
| 24-Apr | **51** | 780 | 4 | 99.49 | 3 | 99.62 | <1 | 100.00 | 1 | 99.87 | <1 | 100.00 | 1 | 99.87 | 0 | 100.0 |
| 26-Apr | **53** | 490 | <1 | 100.00 | 2 | 99.59 | 8 | 98.37 | <1 | 100.00 | 10 | 97.96 | <1 | 100.00 | 35 | 92.9 |
| 29-Apr | **56** | 320 | <1 | 100.00 | <1 | 100.00 | 88 | 72.50 | <1 | 100.00 | 50 | 84.38 | <1 | 100.00 | 20 | 93.8 |
| 30-Apr | **57** | 370 | <1 | 100.00 | <1 | 100.00 | 90 | 75.68 | <1 | 100.00 | 50 | 86.49 | <1 | 100.00 | 50 | 86.5 |
| **Average** | | **388** | **1** | **99.82** | **1** | **99.70** | **37** | **89.58** | **1** | **99.81** | **30** | **90.98** | **1** | **99.84** | **27** | **91.2** |
| **Sample** | | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 11 | 10 | 11 | 11 | 11 |
| **St. Dev.** | | **189** | **1** | **0.25** | **1** | **0.37** | **33** | **9.09** | **1** | **0.26** | **20** | **6.60** | **1** | **0.30** | **17** | **6.71** |
| **Highest** | | **780** | **4** | **100** | **3** | **100.0** | **90** | **100.0** | **3** | **100.0** | **52** | **100.0** | **2** | **100.0** | **50** | **100.0** |
| **Lowest** | | **160** | **<1** | **99** | **<1** | **98.8** | **<1** | **72.5** | **<1** | **99.3** | **<1** | **80.0** | **<1** | **99.1** | **<1** | **80.0** |

**Table H.16:** Total Coliform Removal Efficiencies of Filters (Run 3)

(Coliform Unit – CFU/100 mL)

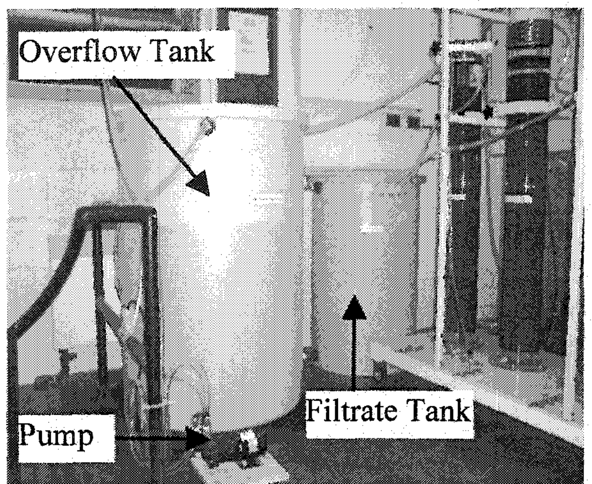
| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 8-May | 2 | 7570 | 162 | 97.48 | 118 | 98.16 | 2120 | 66.98 | 76 | 98.82 | 2124 | 66.92 | 65 | 98.99 | 2110 | 67.13 |
| 9-May | 3 | 6420 | 45 | 98.67 | 41 | 98.79 | 1520 | 55.03 | 10 | 99.70 | 1023 | 69.73 | 10 | 99.70 | 1071 | 68.31 |
| 11-May | 5 | 3380 | <1 | 100.00 | 12 | 99.80 | 1864 | 68.25 | <1 | 100.00 | 2154 | 63.30 | <1 | 100.00 | 1780 | 69.68 |
| 12-May | 6 | 5870 | <1 | 100.00 | <1 | 100.00 | 1724 | 83.29 | 12 | 99.88 | 1620 | 84.30 | <1 | 100.00 | 2344 | 77.29 |
| 14-May | 8 | 10320 | 10 | 99.85 | 10 | 99.85 | 2055 | 69.38 | <1 | 100.00 | 1819 | 72.90 | 8 | 99.88 | 840 | 87.49 |
| **Average** | | **6712** | **43** | **99.20** | **36** | **99.32** | **1857** | **68.59** | **20** | **99.68** | **1748** | **71.43** | **17** | **99.71** | **1629** | **73.98** |
| **Sample** | | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| **St. Dev.** | | **2532** | **68** | **1.11** | **48** | **0.81** | **244** | **10.04** | **32** | **1** | **461** | **8.02** | **27** | **0.42** | **651** | **8.53** |
| **Highest** | | **10320** | **162** | **100.0** | **118** | **100.0** | **2120** | **83.3** | **76** | **100** | **2154** | **84.3** | **65** | **100.0** | **2344** | **87.5** |
| **Lowest** | | **3380** | **<1** | **97.5** | **<1** | **98.2** | **1520** | **55.0** | **<1** | **98** | **1023** | **63.3** | **<1** | **99.0** | **840** | **67.1** |

**Table H.17:** *E. coli* Removal Efficiencies of Filters (Run 3)

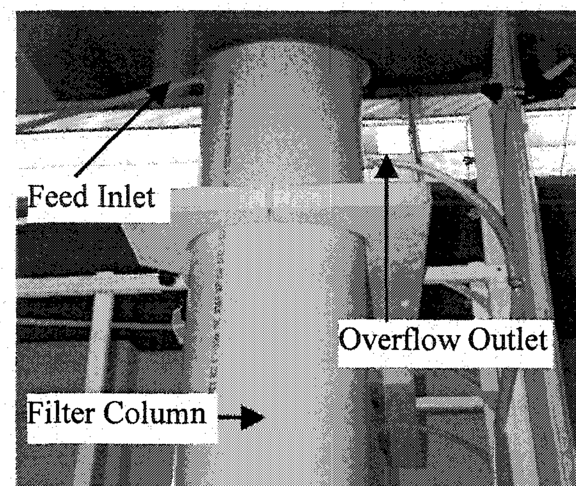
(*E. coli* Unit – CFU/100 mL)

| Date | Day | Feed | Filter 1 | | Filter 2 | | | | Filter 3 | | | | Filter 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (16h) | Total | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. | Total | % Rem. | Fabric | % Rem. |
| 8-May | 2 | 1080 | 12 | 98.9 | 4 | 99.6 | 214 | 80.2 | 3 | 99.7 | 188 | 82.6 | 2 | 99.8 | 154 | 85.7 |
| 9-May | 3 | 820 | <1 | 100.0 | <1 | 100.0 | 65 | 92.1 | <1 | 100.0 | 50 | 93.9 | <1 | 100.0 | 60 | 92.7 |
| 11-May | 5 | 190 | 2 | 98.9 | 1 | 99.5 | 12 | 93.7 | 2 | 98.9 | 21 | 88.9 | 1 | 99.5 | <1 | 100.0 |
| 12-May | 6 | 370 | 1 | 99.7 | <1 | 100.0 | <1 | 100.0 | <1 | 100.0 | <1 | 100.0 | <1 | 100.0 | 2 | 99.5 |
| 14-May | 8 | 990 | <1 | 100.0 | <1 | 100.0 | 3 | 99.7 | <1 | 100.0 | <1 | 100.0 | <1 | 100.0 | <1 | 100.0 |
| **Average** | | **690** | **3** | **99.5** | **1** | **99.8** | **59** | **93.13** | **1** | **99.7** | **52** | **93.09** | **1** | **99.86** | **43** | **95.6** |
| **Sample** | | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| **St. Dev.** | | **391** | **5** | **0.55** | **2** | **0.25** | **91** | **8.05** | **1** | **0.46** | **79** | **7.48** | **1** | **0.23** | **67** | **6.31** |
| **Highest** | | **1080** | **12** | **100.0** | **4** | **100.0** | **214** | **100.0** | **3** | **100.0** | **188** | **100.0** | **2** | **100.0** | **154** | **100.0** |
| **Lowest** | | **190** | **<1** | **98.9** | **<1** | **99.5** | **<1** | **80.2** | **<1** | **98.9** | **<1** | **82.6** | **<1** | **99.5** | **<1** | **85.7** |

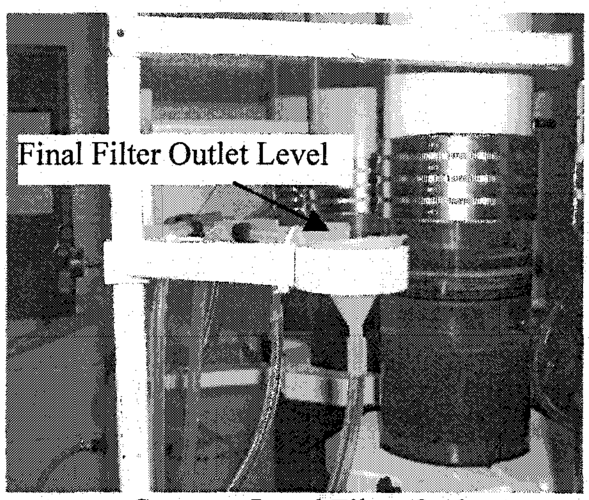
## APPENDIX I: Additional Pictures of Experimental Setup



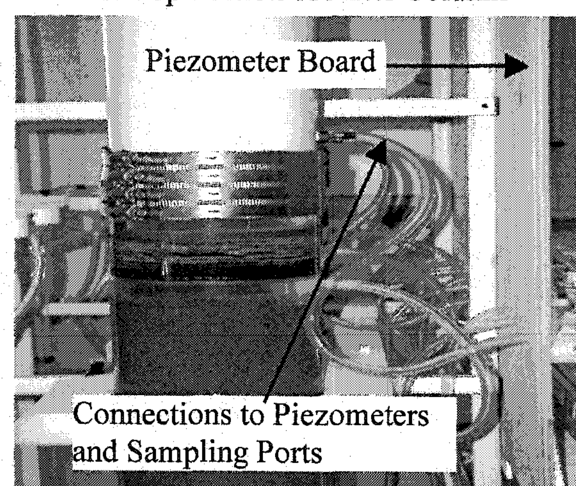

a. Overflow and Filtrate Tank



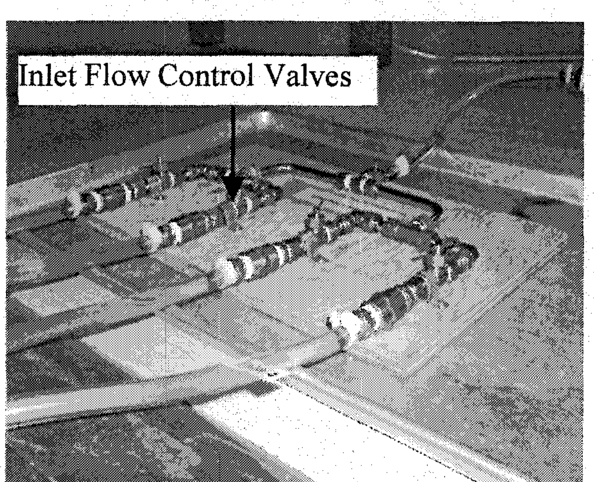

b. Top Portion of Filter Column



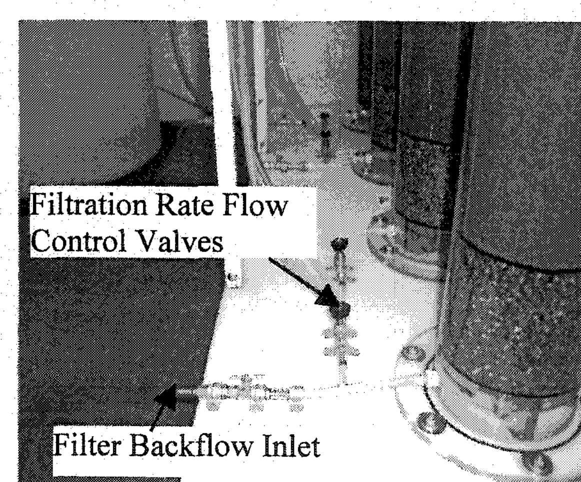

c. Constant Level Filter Outlet




d. Connections to the Piezometers




e. Feed Distribution Manifold




f. Filter Outlet and Base Plate

**Plate I.1:** Different Parts of Experimental Setup

## APPENDIX J: Treated Wastewater Effluent Characteristics

**Table J.1:** Treated Wastewater Effluent Characteristics

| Date | TOC (mg/L) | Ammonia-Nitrogen (mg/L) | Total Coliform (CFU/100 mL) | Fecal Coliform (CFU/100 mL) | *E. coli* (CFU/100 mL) |
|---|---|---|---|---|---|
| | | | | | |
| 6-Jan | 28.45 | | 2800000 | 467000 | |
| 12-Jan | 33.87 | | 1155000 | 236600 | |
| 19-Jan | 30.32 | | 785000 | 113000 | |
| 2-Mar | 35.92 | 48.8 | 1732000 | | 104000 |
| 8-Mar | 32.19 | 37.9 | 1137000 | | 85000 |
| 15-Mar | 29.45 | 51.2 | 856000 | | 110000 |
| 22-Mar | 36.49 | 46.7 | 2109000 | | 733000 |
| 29-Mar | 35.34 | 53.1 | 2260000 | | 455000 |
| 5-Apr | 28.92 | 39.4 | 773000 | | 118000 |
| 12-Apr | 34.56 | 55.4 | 547000 | | 74800 |
| 19-Apr | 33.89 | 57.5 | 804000 | | 91500 |
| 26-Apr | 36.15 | 45.8 | 2755000 | | 321000 |
| 4-May | 29.5 | 47.2 | 1252000 | | 178000 |
| 11-May | 32.4 | 36.8 | 895000 | | 85000 |
| **Average** | **32.68** | **47.3** | **1418600** | **272200** | **214100** |
| **Sample** | 14 | 11 | 14 | 3 | 11 |
| **Highest** | 36.49 | 57.5 | 2800000 | 467000 | 733000 |
| **Lowest** | 28.45 | 36.8 | 547000 | 113000 | 74800 |
| **St. Dev.** | 2.89 | 6.96 | 769612 | 179665 | 209758 |

St. Dev. – Standard Deviation.

Treated wastewater effluent was collected from Lou Romano Wastewater Reclamation Plant, Windsor, Ontario. The effluent was collected before the disinfection point.

# APPENDIX K: Calibration Curves

## *K.1 Total Carbon (TC) and Inorganic Carbon (IC) Standard Curve*

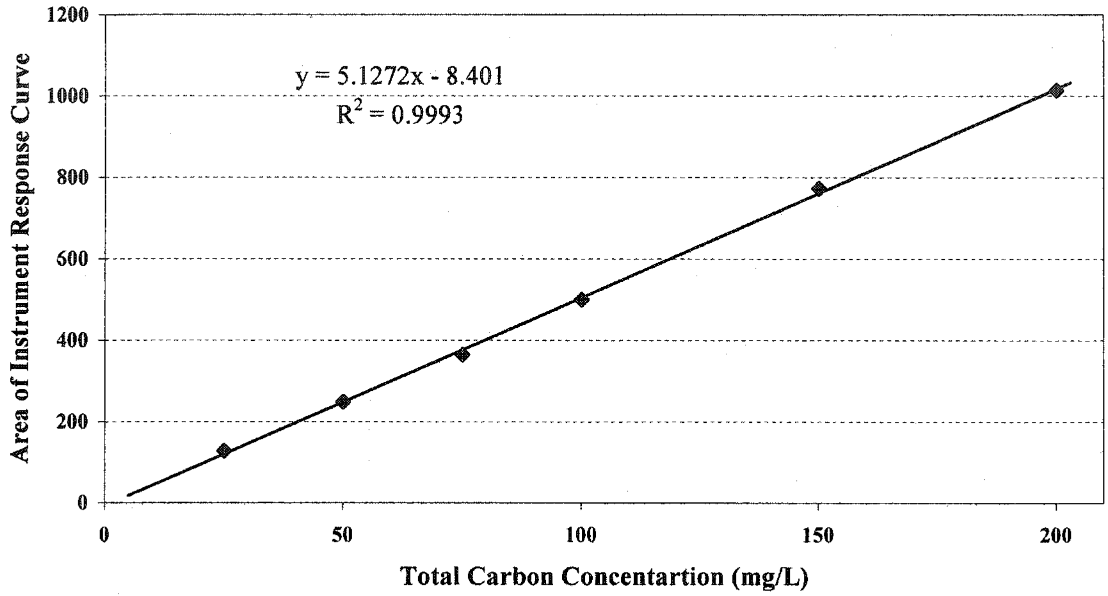



**Figure K.1:** TC Calibration Curve 1 for Simadzu TOC-VCSH Carbon Analyzer (Injection Volume 50 microlitres; Prepared on 20 December 2003)

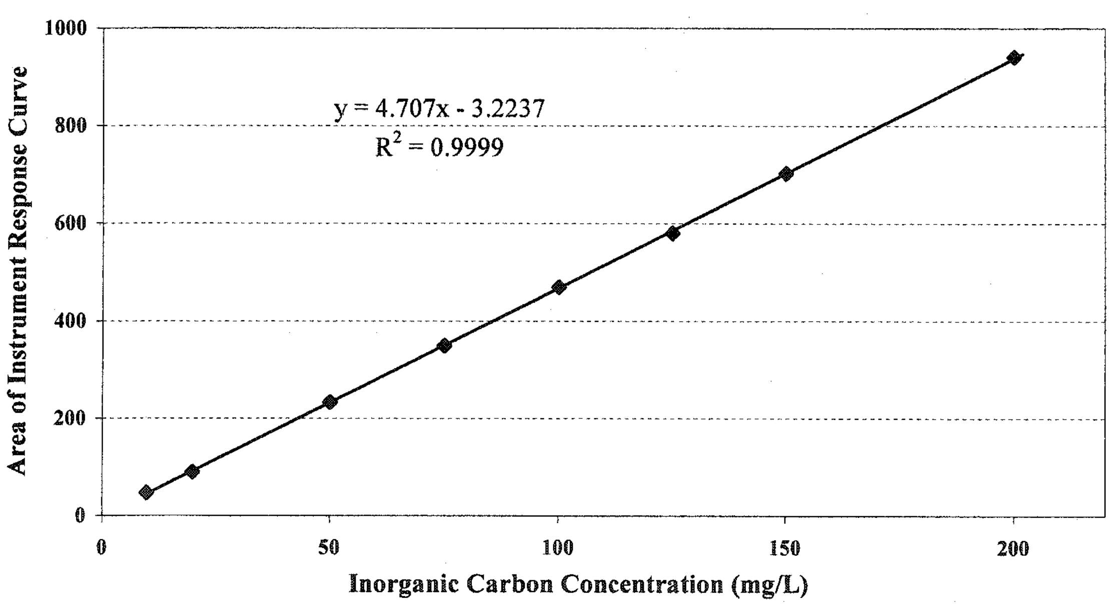



**Figure K.2:** IC Calibration Curve 1 for Simadzu TOC-VCSH Carbon Analyzer (Injection Volume 50 microliter; Prepared on 20 December 2003)

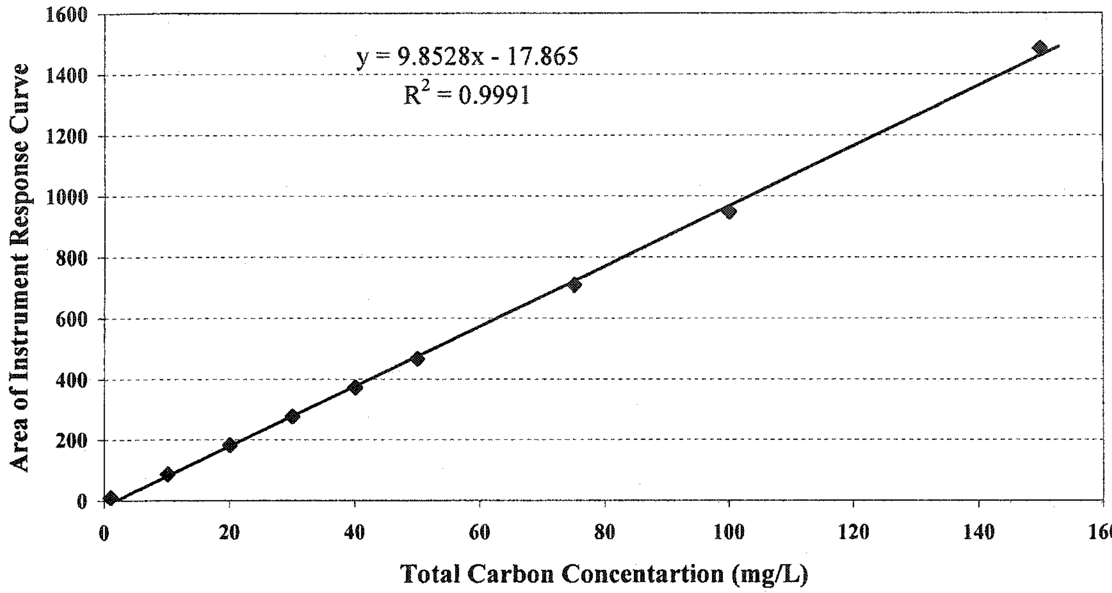



**Figure K.3:** TC Calibration Curve 2 for Simadzu TOC-VCSH Carbon Analyzer (Injection Volume 100 microliter; Prepared on 1 April 2004)

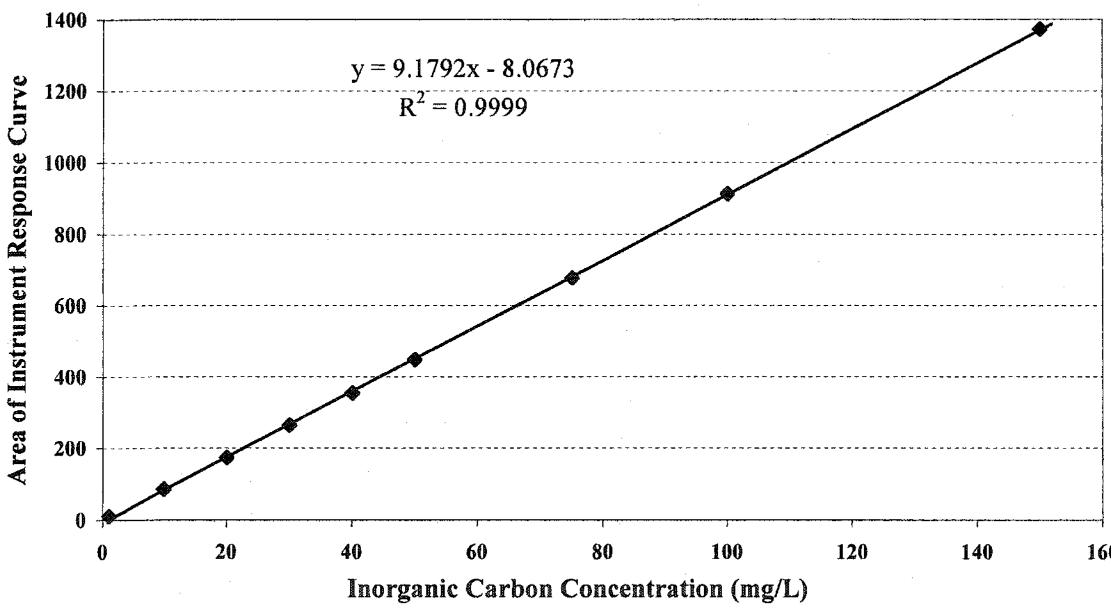



**Figure K.4:** IC Calibration Curve 2 for Simadzu TOC-VCSH Carbon Analyzer (Injection Volume 100 microliter; Prepared on 1 April 2004)

### *K.2 Nitrate-Nitrogen Standard Curve*

For Orion Research ISE 93-07 and Orion Research 290A Ion Analyser

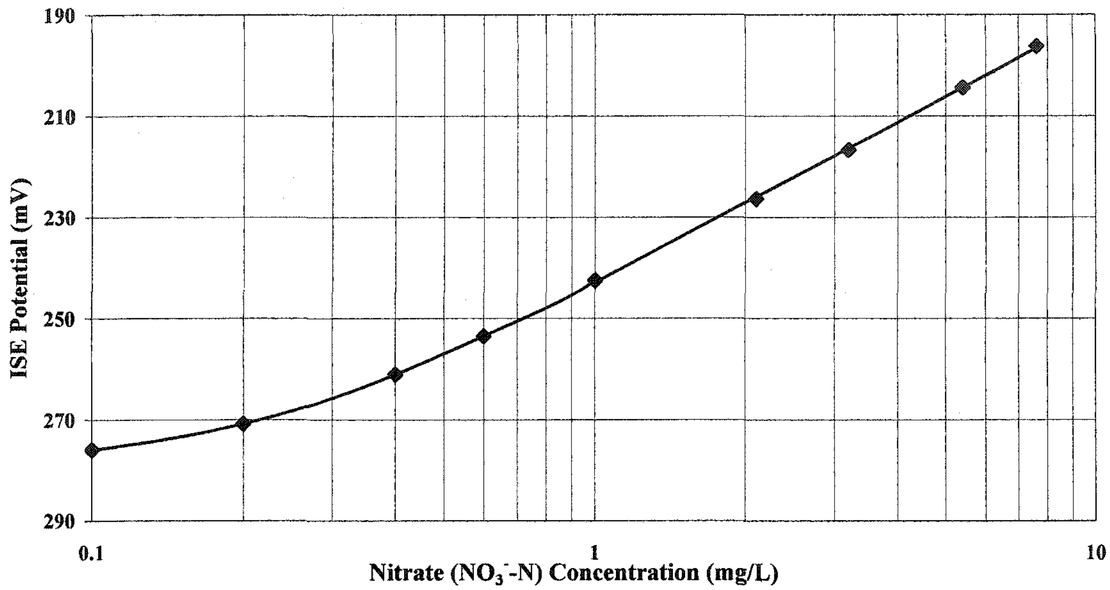



**Figure K.5:** Calibration Curve for Nitrate ($NO_3^-$ -N)

### *K.3 Ammonia-Nitrogen Standard Curve*

For Accumet Ammonia Gas Sensing Electrode and Orion Research 290A Ion Analyser

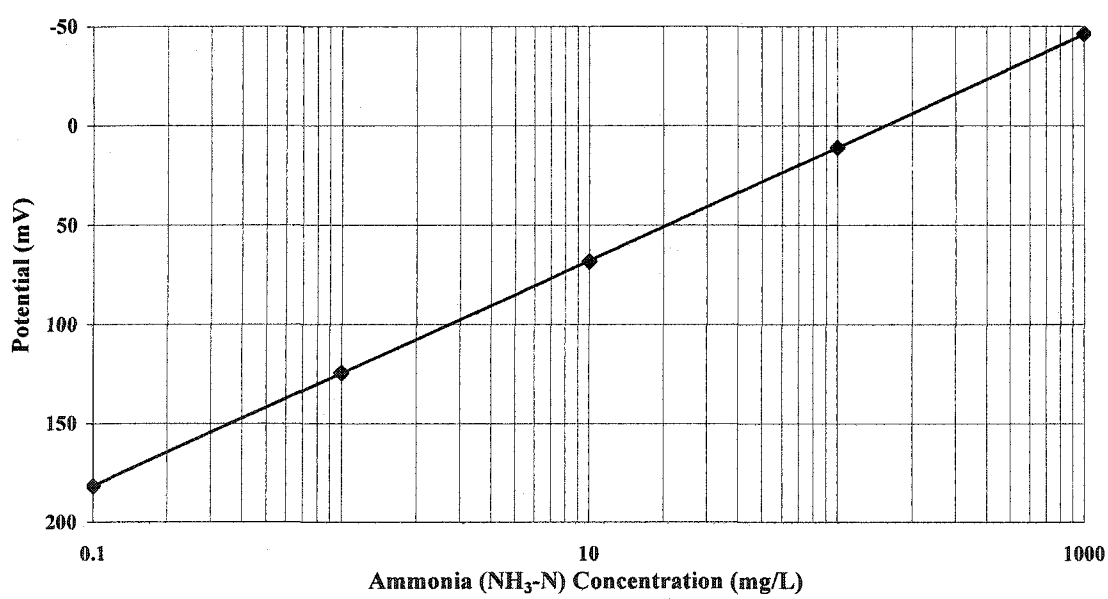



**Figure K.6:** Calibration Curve for Ammonia ($NH_3$-N)

## VITA AUCTORIS

| | |
|---|---|
| **NAME** | **Pulin Kumar Mondal** |
| **PLACE OF BIRTH** | Dhaka, Bangladesh |
| **YEAR OF BIRTH** | 1975 |
| **EDUCATION** | Civil Aviation High School, Dhaka, Bangladesh<br>1985 – 1989. Secondary School Certificate (Science) |
| | Dhaka College, Dhaka, Bangladesh<br>1990 – 1992. Higher Secondary Certificate (Science) |
| | Bangladesh University of Engineering and Technology (BUET), Dhaka, Bangladesh<br>1994 – 1999. B. Sc. (Civil Engineering) |
| | University of Windsor, Windsor, Ontario, Canada<br>2002 – 2004. M. A. Sc. (Environmental Engineering) |